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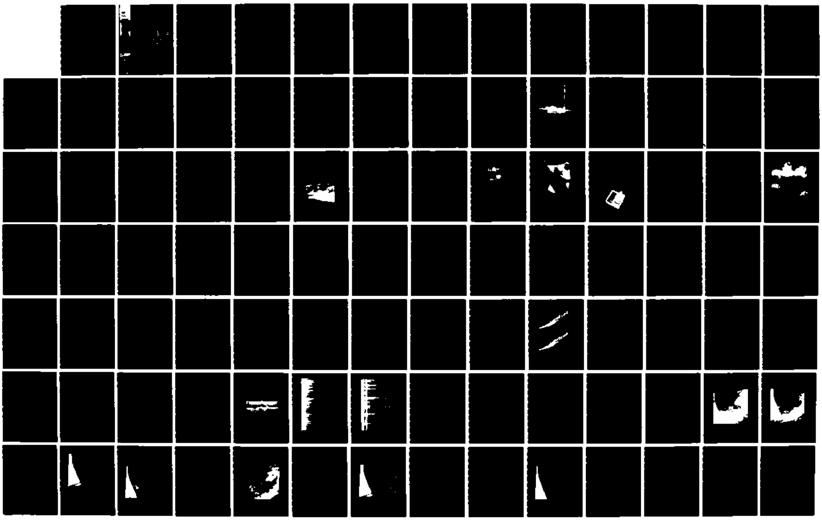

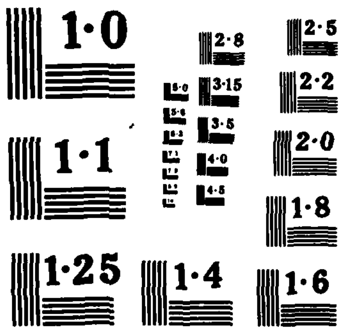
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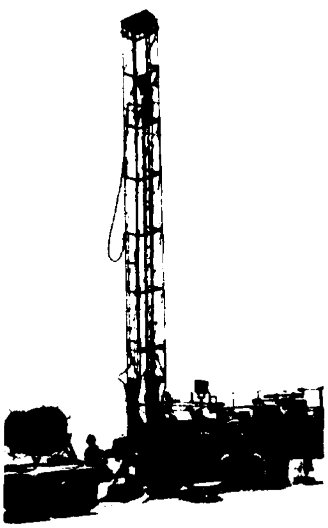

# PROCEEDINGS OF THE GROUND-WATER DETECTION WORKSHOP, 12-14 JANUARY 1982, VICKSBURG, MISSISSIPPI

Compiled by

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DEPARTMENT OF THE ARMY
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December 1984

Final Report

Approved For Public Release. Distribution Unlimited



Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under Project No. 4A762719AT40
Task Area C0, Work Unit 017

Cosponsored by US Army Engineer Waterways Experiment Station
PO Box 631, Vicksburg, Mississippi 39180-0631

and

US Army Belvoir Research and Development Center
Fort Belvoir, Virginia 22060-5605

# MILITARY HYDROLOGY REPORTS

| Report No. | No. in Series | Title | Date |
|---|---|---|---|
| TR EL-79-2 | - | Proceedings of the Military Hydrology Workshop, 17-19 May 1978, Vicksburg, Mississippi | May 1979 |
| MP EL-79-6 (Military Hydrology Series) | 1 | Status and Research Requirements | Dec 1979 |
| | 2 | Formulation of a Long-Range Concept for Streamflow Prediction Capability | Jul 1980 |
| | 3 | A Review of Army Doctrine on Military Hydrology | Jun 1981 |
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| | 5 | A Quantitative Summary of Groundwater Yield, Depth, and Quality Data for Selected Mideast Areas (U) | Mar 1982 |
| | 6 | Assessment of Two Currently "Fieldable" Geophysical Methods for Military Ground-Water Detection | Oct 1984 |
| | 7 | A Statistical Summary of Ground-Water Yield, Depth, and Quality Data for Selected Areas in the CENTCOM Theatre of Operations (U) | Oct 1984 |
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A Ground-Water Detection Workshop, cosponsored by the US Army Engineer Waterways Experiment Station and the US Army Mobility Equipment Research and Development Command (became US Army Belvoir Research and Development Center, October 1983), was held in Vicksburg, Miss., 12-14 January 1982. The purpose of the workshop was to establish research and development priorities and taskings. Ground-water detection specialists representing various Federal agencies

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20. ABSTRACT (Continued).

and the academic community were in attendance. The workshop participants presented technical papers concerning ground-water supply requirements and ground-water detection technology. This report also contains a summary of the results of group discussions and the identification of proposed research priorities for:

a. Database and remote sensing requirements.

b. Geophysical requirements.

## PREFACE

A Ground-Water Detection Workshop cosponsored by the US Army Engineer Waterways Experiment Station (WES) and the US Army Mobility Equipment Research and Development Command (MERADCOM) was held in Vicksburg, Miss., on 12-14 January 1982. MERADCOM became the US Army Belvoir Research and Development Center in October 1983. This report was published under Department of the Army Project No. 4A762719AT40, "Mobility, Soils, and Weapons Effects Technology," Task Area CO, "TO Construction," Work Unit 017, "Remote Procedures for Locating Water Supplies," sponsored by the Office, Chief of Engineers (OCE), US Army. Technical Monitors for OCE during the workshop and preparation of these proceedings were Mr. Walter Swain and Dr. Clemens A. Meyer.

Papers were presented by the following persons: CPT(P) W. T. Broadwater, MERADCOM; Dr. Ran Gerson, Hebrew University; Dr. Steven A. Arcone, US Army Cold Regions Research and Engineering Laboratory; Mr. Gerald K. Moore, Dr. Robert L. Laney, and Dr. Adel A. R. Zohdy, US Geological Survey; Mr. Melvin B. Satterwhite, US Army Engineer Topographic Laboratories; and Dr. Lewis E. Link, Jr., Dr. Dwain K. Butler, Mr. Jerry R. Lundien, Dr. Paul F. Hadala, and Mr. John H. Shamburger, all of the WES.

The presentations by WES personnel were prepared under the general supervision of Dr. John Harrison, Chief, Environmental Laboratory (EL), and Mr. Bob O. Benn, Chief, Environmental Systems Division (ESD), EL. CPT(P) Broadwater was responsible for MERADCOM participation in the workshop. The WES individuals who coordinated and managed the workshop were Dr. Link and Mr. John G. Collins, both of ESD. Mr. Elba A. Dardeau, Jr., ESD, compiled this report on the proceedings.

COL Tilford C. Creel, CE, was Commander and Director of WES at the time of the workshop and during preparation of these proceedings. Mr. F. R. Brown was Technical Director.

This report should be cited as follows:

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CONTENTS

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GROUND-WATER DETECTION WORKSHOP

12-14 January 1982

Vicksburg, Mississippi

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| MAJ Edward Wages | Commandant<br>US Marine Corps<br>ATTN: Code LME-2<br>Washington, DC 20380 |
| Dr. Adel A. R. Zohdy | US Geological Survey<br>Electromagnetism and Geomagnetism Branch<br>Mail Stop 964<br>PO Box 25046<br>Denver Federal Center<br>Denver, CO 80225 |

AGENDA

GROUND-WATER DETECTION WORKSHOP

12-14 January 1982

Vicksburg, Mississippi

Tuesday, 12 January

| | | |
|---|---|---|
| 0830 | Arrive at Workshop | |
| 0845 | Opening Remarks | Dr. Lewis E. Link, Jr., WES |

SESSION I: REVIEW OF REQUIREMENTS

| | | |
|---|---|---|
| 0900 | Military Water-Supply Requirements | CPT(P) W. T. Broadwater MERADCOM |
| 0930 | Water Database Requirements | Dr. Lewis E. Link, Jr., WES |
| 1000 | Discussion | |
| 1015 | Break | |

SESSION II: REVIEW OF TECHNOLOGY

| | | |
|---|---|---|
| 1030 | Ground-Water Occurrence in the Middle East | Dr. Ran Gerson, Hebrew University |

Status of Geophysical Techniques

| | | |
|---|---|---|
| 1100 | St[illegible] [illegible]hysical Methodology for Ground-Wat[illegible] Detection | Dr. Dwain K. Butler, WES |
| 1130 | Electrical Resistivity Techniques* | Dr. Adel A. R. Zohdy, USGS, Denver |
| 1200 | Lunch | |

Status of Radar/Microwave Techniques

| | | |
|---|---|---|
| 1300 | Ground-Water Detection: Radar Measurements of Soil Electrical Properties | Mr. Jerry R. Lundien, WES |
| 1330 | Radar Detection of Ground Water | Dr. Steven R. Arcone, CRREL |

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* Presentation not submitted for inclusion in these proceedings.

GROUND-WATER OCCURRENCE IN THE MIDDLE EAST

by

Dr. Ran Gerson*

The Middle East receives less than 6 in. of mean annual precipitation. Much of the stratigraphic section is exposed; therefore, geologic features, such as lithology or structure, can be related to the possible occurrence of ground water.

From a hydrologic point of view, the stratigraphic section of this area is relatively simple. First, we have the Precambrian basement complex, which consists of generally impervious igneous and metamorphic rock units. Although the Precambrian units are fissured, jointed, and faulted, in general, they do not contain much ground water. Above the basement complex is the lower clastic division, a very pervious, relatively thick (a few hundred metres) unit consisting of sandstones, mudstones, and some carbonates and conglomerates. Above the lower clastic division and through the upper Cretaceous and lower Tertiary sections is a middle marine carbonate unit of limestones, dolomites, chalks, marls, and shales that has about the same thickness. Above are upper Tertiary and Quaternary sandstones, conglomerates, limestones, and gravels comprising the upper clastic division. So we actually have two mainly marine clastic units, with a carbonate unit between them, all of which overlie the basement complex.

Outcrops are continuous and overlie the same basement complex throughout some areas of Saudi Arabia, the southern Sinai, southern Egypt, and southern Libya. To the north are sandstones skirting the basement complex in very narrow belts, followed by the carbonates, and then the upper clastic division, with sand dunes, conglomerates, gravels, or lacustrine surface materials. So, the view from south to north in the region that extends from Saudia Arabia all the way into Algeria, Morocco, and Tunisia is from older to younger strata.

The major aquifer in the north is near the coast. Water flows either overland or underground from the carbonate terrains of the Negev and Sinai toward the Mediterranean. Surface materials along the coast consist mainly of sand dunes overlying clays, gravels, or other loose materials. A geologic cross section of the coastal area of the Sinai shows a repetitive sequence of

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* Hebrew University, Jerusalem, Israel.

the TAC. The recommendations made were: that ETL either obtain a software system compatible with existing equipment or acquire a combined software/hardware system. The study included time and cost estimates needed for input to the water resource databases that already exist at ETL and the WES.

WATER DATABASE REQUIREMENTS

by

Dr. Lewis E. Link, Jr.

An automated water resources database and associated geographic information system is needed for support of Rapid Deployment Joint Task Force (RDJTF)* Engineer missions and responsibilities. A study was conducted by the Department of Geography of the State University of New York at Buffalo** to develop recommendations concerning existing, commercially available geographic information systems suitable for installation and operation at the U. S. Army Engineer Topographic Laboratories (ETL), Fort Belvoir, Virginia. The database specifications and RDJTF requirements were reviewed to establish geographic information system selection criteria. The criteria that were established pertained to four factors: (a) system technical capabilities, (b) developing organization experience and capabilities, (c) client comments, and (d) costs. Based on these criteria, seven systems were selected, evaluated, and ranked in terms of their overall suitability. The purpose of the study was to recommend one or more geographic information systems suitable for installation at the ETL Terrain Analysis Center (TAC) at the earliest possible date.

Using an interpretive procedure developed by the Waterways Experiment Station (WES), the TAC produced ground-water supply potential overlays for the 1:250,000-scale Joint Operations Graphic Sheets based on existing data. Currently, these overlays are produced manually on a mylar base by ETL/TAC.

The first objective for a geographic information system is to automate the water database to provide the capability for rapid querying in support of proposed RDJTF operations. Additionally, computer-generated maps similar to the present overlays will be produced by the system. A second objective for the geographic information system is to automate other mapping activities at

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* The RDJTF was redesignated the US Central Command (CENTCOM) on 1 January 1983. CENTCOM whose area of responsibility includes eastern Africa and southwestern Asia, is headquartered at MacDill AFB, Fla.

** Calkins, H. W., and Johnson, T. R. 1981. "Military Hydrology; Report 4, Evaluation of an Automated Water Data Base for Support to the Rapid Deployment Joint Task Force (RDJTF)," Miscellaneous Paper EL-79-6, prepared by Department of Geography, State University of New York at Buffalo, for the US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

trained with it much to date. As you probably know, well drilling is as much an art as a science, and there is no substitute for experience. We just do not have experienced operators yet.

The last consideration that the Engineer School had concerning subsurface water-detection system was the power requirements. The power for the system must be either self-contained or compatible with standard military generators. If we propose a system that requires precise power, then we must either supply a battery pack or provide a regulator on the equipment if AC precision power is used. This is an important consideration, especially if minicomputers are used to aid in data interpretation.

As I pointed out earlier, the acceptability of the technologies or equipment systems that our organization recommends for use in the detection of ground water will be determined after more detailed analyses of the technology candidates, taking into account the considerations I have covered today, including the affordability in terms of cost both for the equipment and to the force structure, and their applicability to the field forces in various potential scenarios.

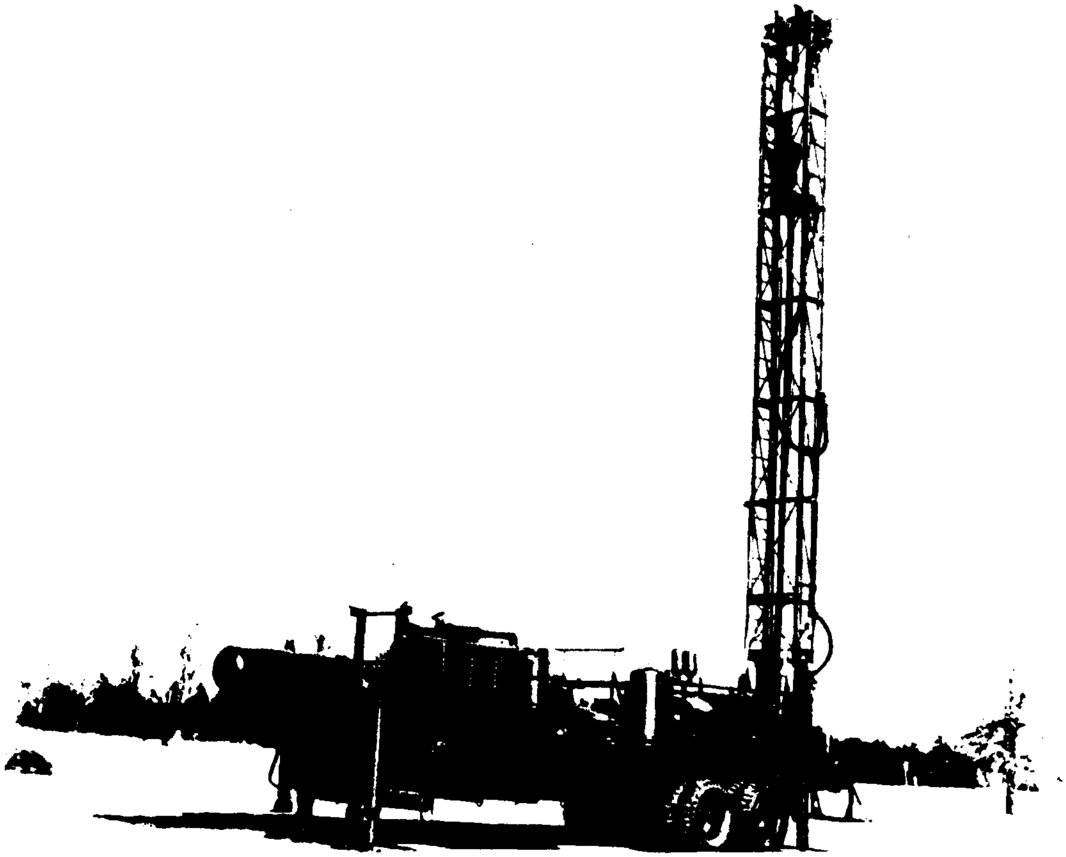

Figure 1. Army inventory 1500-ft drilling rig

- O 1500-FT DEEP, 6-INCH NORMAL DIAMETER WELL
- O COMPLETION EQUIPMENT FOR 2 1500-FT WELLS
- O ANY TERRAIN - SOIL, ROCK, OTHER GEOLOGICAL FORMATION
- O MUD, AIR AND FOAM CIRCULATION
- O 50-GPM FLOW AT 1200 FT
- O DOWN HOLE AIR HAMMER DRILLING
- O AIR TRANSPORTABLE (C-130)
- O TOWABLE-SEMI-TRAILER OR 5-TON TRUCK (USING DOLLY)

Figure 2. Well-drilling machine capabilities

would like for any equipment going to the field to be capable of field calibration and self-test potential, as well as be reliable and maintainable. Reliability and maintenance refer to mean time between failure (MTBF), meaning that the equipment has to be sent some place else for repairs. The Engineer School would like to have a minimum of 250 hr of operational MTBF. However, if the best we can offer to the Army, Air Force, and Marine Corps is 150 hr of operation MTBF, then they will have to decide if this MTBF will satisfy their needs.

The next consideration is size, mobility, and transportability. This equipment has got to be air transportable, preferably on no more than one aircraft. Some of the systems that are currently used for oil exploration, such as the vibrator trucks for seismic reflection, for example, are too large and too sophisticated for field military application. [Comment from LTC Barcomb, REDCOM: "The equipment should fit in a C141 aircraft." Comment from LTC Pellek, HQ USAF: "Better yet in a C130 aircraft; better yet, a Huey (UH1 helicopter)."] The common goal of both MERADCOM and the Engineer School is to keep the equipment as small and as easily deployable as possible. The equipment will be used in a direct support reconnaissance mission prior to well drilling and must be compatible with well-drilling equipment capabilities. For those of you who are not familiar with the well-drilling capabilities of the field Army, the Air Force, or the Marine Corps, this is a picture of the 1500-ft* well-drilling rig that is currently in our inventory (Figure 1). One reason that we are trying to get the detection equipment down to a manageable size is that to deploy this well-drilling capability with everything that goes with it--including the rig, the truck to pull it, the drilling steel, the mud, and the down hole equipment to drill and complete two 1500-ft depths and a 50-gpm pumping rate (Figure 2)--takes five C130 aircraft. So that gives you an idea of the type of equipment we have.

Another area of concern is that currently we do not have the kind of trained people that are needed to operate that drill rig. Although there are well-drilling TOE units, the training that those people have had, with the exception of one group in the Reserves, has not been extensive. Two active units have just gotten their equipment in the last 6 months, but they have not

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* A table of factors for converting US customary units of measurement to metric (SI) units is presented on page 12.

To summarize, the three ground-water detection recommendations, which are given as top priority water support R&D areas to the Chairman of the Joint Chiefs of Staff, include:

a. A data bank for potential ground-water and surface-water sources or what we already know about water-supply systems in certain areas of the world.

b. Coupling what we already know with a supplemental data bank of potential water sources by analysis of remote sensor data. (The DSB recommends using satellite imagery, aerial photography, etc.,

c. Development of subsurface water detectors.

Both near-term (1-3 years) and mid-term (4-5 years) technology recommendations were included in the DSB report. Near-term recommendations were to pursue electrical resistivity, seismic refraction, and ground-penetrating radar systems to solve the problem. The mid-term recommendations were to investigate seismic reflection, loop-loop electromagnetic, and self-potential technologies. The recommendations are subject to a more thorough review; however, they were based on the best available data. Although the overall report is classified SECRET, the section on ground-water detection is UNCLASSIFIED, and can probably be made available for those of you who want to see what type of analysis was done. LTC Dearden, JCS/J4, has the releasing authority.

Unfortunately, a representative of the Engineer School (also located at Fort Belvoir) was unable to attend this workshop to discuss considerations for subsurface water-detection equipment. We did coordinate very closely with the Engineer School and, at their request, I will summarize the list of considerations for subsurface water-detection equipment. Before I review these general considerations, I would like to draw your attention to one consideration in particular--acceptability will be determined after further analyses of technology candidates, costs, and potential scenarios.

First, the factors that have to be considered are the ease of operation, the operator skills, and data interpretation. Initially, we will not likely have sophisticated data interpretation capability in field engineer units. The Army and the other services want the operator skills to be as minimal as possible. We will not be able to send out teams of trained geophysicists to do this kind of work. Consequently, emphasis must be placed on minimizing the operator/interpreter requirements.

Next, the ease of calibration, reliability and maintenance, and shelf life for field applications are extremely important. The Engineer School

# MILITARY WATER-SUPPLY REQUIREMENTS

by

CPT(P) W. T. Broadwater*

Good morning, I am CPT Tom Broadwater, R&D Coordinator for the Energy and Water Resources Laboratory of MERADCOM at Fort Belvoir, Virginia. MERADCOM is an acronym that stands for the US Army Mobility Equipment Research and Development Command. We are equipment oriented and are under the US Army Materiel Development and Readiness Command (DARCOM). I will discuss the military water-supply requirements relative to ground-water detection.

The combat developer representing the user community--usually, one of the proponent schools within the US Army Training and Doctrine Command (TRADOC)--establishes a requirement or a need for a particular capability to support the field military forces. The materiel developer within DARCOM then provides particular technologies or sets of equipment to satisfy a user with the desired field capability.

Along these lines, I want to show you what we have accomplished and to familiarize you with what we now have in the way of limited requirements. First, we have a Science and Technology Objective (STO), which is the primary basis for our basic research and exploratory development program for improved ground-water detection, well-drilling, and pumping capabilities. The STO is our entire guidance from the Fiscal Year (FY) 1981 Science and Technology Guide (STOG) (published in interim form in FY 1981); it is the formalized requirement document used to obtain funding to develop equipment or to conduct technology research in this area. The second document is a Draft Letter of Agreement (DLOA) for a Subsurface Water Detector. The Engineer School at Fort Belvoir was the proponent school for developing and distributing the DLOA for a subsurface water detector. This DLOA was sent to the military community for comments on its needs for ground-water detection technology or equipment (primarily equipment). In addition to these requirements, the Defense Science Board (DSB) Task Force on Water Support to U. S. Forces in an Arid Environment has provided recommendations in its 21 October 1981 report.

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* US Army Mobility Equipment Research and Development Command, Fort Belvoir, Va., now assigned to Headquarters, US Army Materiel Command, Alexandria, Va.

## OPENING REMARKS

by

Dr. Lewis E. Link, Jr.*

The Corps of Engineers is responsible for finding water to meet the Army's water requirements when existing sources are not adequate. Water supply is perhaps the most serious constraint that we face in desert operations. Although the detection of ground water, particularly in arid regions, has been investigated for centuries, it remains a very difficult problem. A variety of techniques have been used with some success, but none have performed satisfactorily over a wide range of geologic conditions.

In cosponsoring this workshop, the Corps of Engineers and MERADCOM have the objectives of defining the specific efforts that will provide the Army with an interim capability for ground-water detection in the shortest possible time frame and charting a path for generating a more comprehensive capability for the future. For this reason, we have requested the participation of those who have the expertise and experience to help generate this plan now so that work can proceed immediately.

We are very pleased to host this meeting and to have you as our guests. The WES and MERADCOM are strongly committed to this endeavor and to working very closely together to provide the needed capability.

Enjoy your stay in Vicksburg. Please let us know if there is anything we can do to assist you while you are here.

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* US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

The purpose of the workshop was to establish proposed research and development priorities and taskings in two general areas: (a) database and remote sensing requirements and (b) geophysical requirements. Once these proposed priorities and taskings have been established, a coordinated research plan will be developed to specify both the short-term research required to adapt existing ground-water detection technology to military application and the long-term research required to develop more advanced technology.

Pages 9 through 11 present the workshop agenda. Tuesday, 12 January, was devoted to a review of requirements and technology. Speakers presented papers on geophysical, radar/microwave, and imaging techniques; emerging technologies; and geologic constraints on detection methods.

Proposed research priorities for database and remote sensing requirements and geophysical requirements for ground-water detection were considered in group discussions on Wednesday morning, 13 January. On Wednesday afternoon, each group chairman presented conclusions developed by his group to all the workshop attendees. Summaries of the group discussions (pages 141 through 150) are included in these proceedings.

Army representatives met on Thursday morning, 14 January, to develop a coordinated research plan and to identify both short- and long-term research goals.

## PROCEEDINGS OF THE GROUND-WATER DETECTION WORKSHOP, 12-14 JANUARY 1982, VICKSBURG, MISSISSIPPI

### INTRODUCTION

Military hydrology is a specialized field that deals with the effects of surface and subsurface water on planning and conducting military operations. In 1977, the Office, Chief of Engineers, US Army, approved a military hydrology research program; management responsibility was subsequently assigned to the Environmental Laboratory, US Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi.

The objective of military hydrology research is to develop an improved hydrologic capability for the Armed Forces with emphasis on applications in the tactical environment. To meet this overall objective, research is being conducted in four thrust areas: (a) weather-hydrologic interactions, (b) state of the ground, (c) streamflow, and (d) water supply.

Previously published Military Hydrology reports are listed inside the front cover. This report contributes to the water-supply thrust area, which is oriented toward the development of procedures for rapidly locating and evaluating ground-water supplies, particularly in arid regions. Specific work efforts include: (a) the compilation of guidelines for the expedient location of water for human survival, (b) the development of remote imagery interpretation procedures for detecting and evaluating ground-water sources, (c) the evaluation and adaptation of geophysical methods for detecting and evaluating ground-water sources, and (d) the development of automated water-supply analysis and display concepts.

A Ground-Water Detection Workshop, cosponsored by the WES and the US Army Mobility Equipment Research and Development Command (MERADCOM),* was held in Vicksburg, Mississippi, on 12-14 January 1982. Attendees (pages 5 through 8) included 29 representatives from 13 Federal agencies and one university.

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* MERADCOM became the US Army Belvoir Research and Development Center in October 1983.

## CONVERSION FACTORS, US CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

US customary units of measurement used in this report can be converted to metric (SI) units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| feet | 0.3048 | metres |
| feet per second | 0.3048 | metres per second |
| gallons per minute | 3.785412 | cubic decimetres per minute |
| inches | 25.4 | millimetres |
| miles (US statute) | 1.609347 | kilometres |
| pounds (force) per square inch | 6894.757 | pascals |
| pounds (mass) | 0.4535924 | kilograms |
| square inches | 6.4516 | square centimetres |
| square miles | 2.589998 | square kilometres |
| tons (2000 lb, mass) | 907.1847 | kilograms |

## AGENDA (Concluded)

Thursday, 14 January

| | |
|---|---|
| 0830 | Development of Coordinated Research Plan (Army representatives only) |
| 1200 | Adjourn |

## AGENDA (Continued)

### Status of Imaging Techniques

| | | |
|---|---|---|
| 1345 | Ground-Water Detection Using Landsat Imagery | Mr. Gerald K. Moore, USGS, EROS Data Center |
| 1400 | Using Vegetation as Indicators of Near-Surface Ground Water in an Arid Environment | Mr. Melvin B. Satterwhite, ETL |
| 1415 | Break | |

### Status of Emerging Technologies

| | | |
|---|---|---|
| 1430 | Projectile Penetration Technology Applied to Ground-Water Detection | Dr. Paul F. Hadala, WES |
| 1445 | Emerging Technology: Geophysics | Dr. Dwain K. Butler, WES |
| 1500 | Overview of Advanced Elect omagnetic Techniques for Ground-Water Exploration | Dr. Lewis E. Link, Jr., WES |

### Geologic Constraints on Detection Methods

| | | |
|---|---|---|
| 1515 | Geologic Constraints on Geophysical Surveys for Ground-Water Exploration | Mr. John H. Shamburger, WES |
| 1530 | Ground-Water Availability in Southwest Asia--Evaluation of Geologic and Hydrologic Data | Dr. Robert L. Laney, USGS, Reston |

### Wednesday, 13 January

SESSION III: GROUP DISCUSSION AND IDENTIFICATION OF PROPOSED RESEARCH PRIORITIES

| | | |
|---|---|---|
| 0830 | Group A: Database and Remote Sensing Requirements | Dr. Lewis E. Link, Jr., Chairman |
| | Group B: Geophysical Requirements | Dr. Paul F. Hadala, Chairman |
| 1200 | Lunch | |
| 1430 | Completion of Group Discussions (Chairmen present conclusions to all attendees) | |
| 1600 | Adjourn | |

sands and clays, suggesting the possibility of a number of aquifers all the way down the stratigraphic section--a phreatic one at the top, then semi-confined and confined aquifers until we get to upper Tertiary clays. Fresh water is found principally near the ground surface; however, the ground water becomes increasingly saline down the section. Wells up to 7 m in depth will provide fresh water with less than 800 ppm total dissolved solids. In many places near the coast, all one has to do is to dig a hole. At about 0.5 km from the coast, the top of the saltwater layer is far enough below the lens of fresh water so to not affect a shallow well. The upper aquifer usually has 110 ppm of chlorides and the lower aquifer, 1700 (or more) ppm; therefore, the ground water becomes increasingly saline with depth in the coastal areas.

Ground-water supplies can also accumulate along the coast where large catchments come from the mountainous areas of the Sinai or in similar areas of western Saudi Arabia along the Red Sea. Large alluvial fans--some up to 3800 sq km in size that have a thick lens of fresh water beneath the surface--form in these catchment areas. Oases typically occur in watersheds having areas of more than 500 sq km. Smaller watersheds, particularly those receiving less than 1 in. of mean annual precipitation, generally have small steep fans that do not form appreciable lenses of fresh water. The large fans have a structure of debris flows, gravels, and clays. Wells drilled into these fans should attempt to take advantage of materials with higher transmissivities; however, predicting where such materials will occur is quite difficult. Geophysical methods could probably help in this respect. The water table is usually close to sea level (less than a few metres below the ground surface). Occasionally, as a result of large floods, the lenses of fresh water grow in the upper portions of the fan, and the water table elevation rises 50 to 70 cm or more.

Another good aquifer is the Nubian Sandstone, a very pervious stratum having a thickness of a few hundred metres, lying just above the basement complex and extending throughout all of the mid- and northern Sinai. In most cases, the top of this stratum is a few hundred metres below the ground surface; however, it is exposed at a number of locations. The sandstone dips towards the Mediterranean. Most of the water in this aquifer is old (fossil) water.

A belt of the sandstone lies north of the basement complex in the Sinai,

Egypt, Jordan, and Saudi Arabia. In these areas, large quantities of fresh water penetrated the Nubian Sandstone during the late Pleistocene (i.e., in the last 100,000 years). This fossil water can now be tapped at depths of a few hundred metres to 1000 m below the ground surface. There is an artesian rise, which brings the water in some areas up to within 150 m of the surface. In the southern Sinai, the water ranges from fresh to slightly saline. To the north, the water becomes increasingly saline. Additionally, fewer sandstones and more and more shales and carbonates comprise the strata in the north and in the western desert of Egypt and Libya. The best area for large quantities of fresh water is, therefore, in the southern part of the aquifer. Where erosion cirques, like those in the Negev, or depressions in the western deserts of Egypt occur, water can be found close to the surface. In fact, there are a number of artesian springs associated with the Nubian Sandstone aquifer.

Another source of ground water (both springs and wells) is a unit of Tertiary-Eocene limestones overlying shales. In Israel, Egypt, and Jordan, this unit provides aquifers perched on the shales. Such seepages or springs, occurring along escarpments of the contacts between these strata, are found all around the western and north-central Negev. All of this area drains toward the northwest by a fossil karst system. It is built of Eocene limestones and chalks, overlying the shales that I've discussed earlier. A similar but not identical sequence of interbedded chalks, marls, and limestone dolomites is found within the upper Cretaceous section. In these strata, there are interbedded soft aquicludic marls and shales and hard aquiferic carbonates. Therefore, small confined and perched aquifers can occur in a number of localities.

The basement complex, consisting of igneous or metamorphic units, is very different from the sedimentary beds discussed above. The overlying sedimentary beds contain fresh to brackish water in the Nubian Sandstone, the carbonate aquifers, and the coastal aquifers. In the basement complex, there is very little ground water, perhaps only enough for individual or small unit survival; however, the small quantity of water available is fresh. Although much of the precipitation runs off, some of it infiltrates along joint systems and often surfaces where a valley narrows down to a gorge. Water can thus be absorbed back into the alluvial valley fill. At Santa Catherine Monastery, the water reaches the subsurface by joint systems, and in this area, there are

wells drawing water from both the rock itself and from the very thin alluvial fill that occurs in the local wadis. The yield is minimal--only a few cubic metres per day. An oasis can form where joint systems allow. For example, there is a large spring in the eastern Sinai where the joint system conveys the water toward a stream. The very small pools that occur in this area provide enough water for an aircraft team or a small squad to survive. The carbonate precipitated from these small pools, which can be easily observed from far away, provides a clue that there is or was some water in the area.

A very different situation occurs where the basement complex is skirted by grabens or down-faulted blocks. Along the faultline, barriers form in the Nubian Sandstone aquifer. These barriers can prevent free flow toward the Red Sea and can result in the formation of oases. This pattern repeats itself quite frequently, both in the Sinai and in some places in Saudi Arabia.

Small deposits of water in alluvial materials are of major interest to the survival of small groups. After a flood, some water is absorbed into the alluvium. The interface between the bedrock and the alluvium, if impervious, can trap pools of ground water. A few months after a significant flood, water can be found quite easily on or near the surface. Water can also be found where a waterfall plunges into a canyon. A pool of water can remain at the base of the waterfall even after several months without rain. Such open pools are not always organically clean. However, the ground water located 1 or 2 m away from the pool in adjacent gravel bars, although sometimes containing suspended silts and clays, will generally have less organic material.

Wells are common along stream channels. Water moves along these gravelly channels all the way to the Mediterranean and is available almost all year. For example, in a large catchment called Wadi Peran in the central Sinai, an alluvial aquifer supplies water to a few hundred Bedouins, as well as to 6000 date palms and a few thousand goats and camels. The geologic section consists of late Pleistocene silts and gravels. The average annual replenishment of the aquifer in this area, which is 3.5 km long and about 100 m wide, is 1,000,000 $m^3$. There are more than 40 wells in this wadi, all of which yield fresh water.

Most of the ground-water sources I have just discussed occur in alluvial and especially in igneous terrains and are really freshwater sources, containing from less than one hundred to several hundred parts per million total dissolved solids. These sources are readily rechargeable, and changes in the

elevation of the water table can occur as a result of precipitation patterns. Year-to-year fluctuations can and do occur.

Although gypsum is considered an aquiclude, it can increase the salinity of nearby ground water. The subject of salinity should not be overlooked. In many cases, an aquifer can have the capacity to supply water for 50,000 men; however, rendering the water potable is often a greater problem than locating the water. Potability poses a very serious problem when we require millions of gallons of fresh water per day.

The last water environment I want to discuss is again a localized aquifer. Specifically, where sand dunes rest upon deposits of clays, silts, and marls of the late Pleistocene (e.g., playa materials and mudflats), a localized aquifer can form. In Saudi Arabia and in the Sinai, sand dunes overlie Holocene (20,000-year-old) clay lake deposits. Local wells or oases can be found in the depressions.

Cisterns and water holes, not only in the wadis but also in other areas of the Middle East, should not be overlooked. Quite a few people, beginning with the Israelites in the 10th century B.C., have diverted hill slope water into water systems. The cisterns can be traced from quite a distance by the piles of chalk, shale, or whatever material was removed when the wells were dug. Aqueducts along the hill slopes lead to either open or closed reservoirs. In some cases, aqueducts have been turned into paths. Functioning wells can also be found on the upstream side of old dams. These old dams are very easy to locate on aerial photographs. After a relatively wet year, old operating deep wells can yield enough water for small units of men.

We don't know much about the yield and salinity levels of the small localized aquifers. Many of these aquifers support a local population, though the people there often have barely enough water to survive (2 ℓ or less per person per day); therefore, these aquifers could not support additional personnel. We do, however, know quite a bit about the salinity levels and yields of large aquifers. A good deal of information is available for the Sinai and the Negev; for North Africa in general, there is some information.

STATUS OF GEOPHYSICAL METHODOLOGY FOR GROUND-WATER EXPLORATION

by

Dr. Dwain K. Butler*

I want to stress the fact that there is no device or black box that can be set on the ground at a given location and, with just the press of a button, determine with a 95-percent probability that potable ground water is present at a depth of X feet. Even in the foreseeable future, there is little likelihood that such a device will be available either in this country or elsewhere (contrary to rumors of a "magical" Soviet device that can do all this). This is a logo I used a few years ago for a cavity detection symposium (Figure 1), symbolizing a black box or "all-seeing eye" that can reveal all subsurface conditions. Such a fanciful dream is no closer to realization now after 5 years of intensive research in the realm of cavity detection than it was at the beginning. However, we can explore for cavities and for ground water, and sometimes we can even detect ground water. In the Corps of Engineers, we are experts at finding out what is beneath the surface (Figure 2). I just wanted to establish our credibility before starting.

For us, in the majority of cases, ground water is usually detected as a matter of course in field investigations not specifically intended for ground-water exploration. I will discuss some of the basic concepts and considerations of geophysical ground-water exploration and then present several case histories to give an idea of what is possible now in the area of ground-water exploration. In the emerging technology session later, I will discuss some possibilities for future approaches to the problem.

Geophysical exploration for ground water refers to surface remote sensing techniques (Figure 3). We look for subsurface structural or stratigraphic indicators of the presence of ground water, or we try to measure a parameter that is an actual physical property of the aquifer itself. These indicators are indirect clues to the presence of ground water. A physical property of the aquifer itself could be a more direct clue of the presence of ground water.

Figure 4, which is a typical cross section of conditions in the Upper Volta region of western Africa, illustrates some of the structural and

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* US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

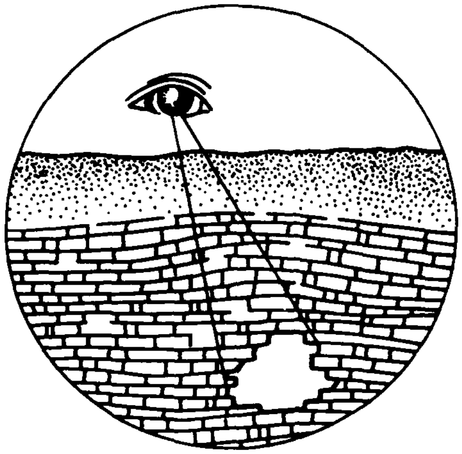

Figure 1. Detection and delineation of subsurface cavities

Figure 2. Two Corps of Engineers experts determining what is beneath the surface

- DIRECT

  DRILLING

- INDIRECT

  AERIAL/SATELLITE REMOTE SENSING

  STRUCTUAL<br>GEOMORPHIC<br>VEGETATIVE — SURFACE INDICATORS

  SURFACE REMOTE SENSING (GEOPHYSICS)

  STRUCTURAL<br>STRATIGRAPHIC — SUBSURFACE INDICATORS

  AQUIFER PROPERTY DETERMINATION

**Figure 3. Exploration for ground water**

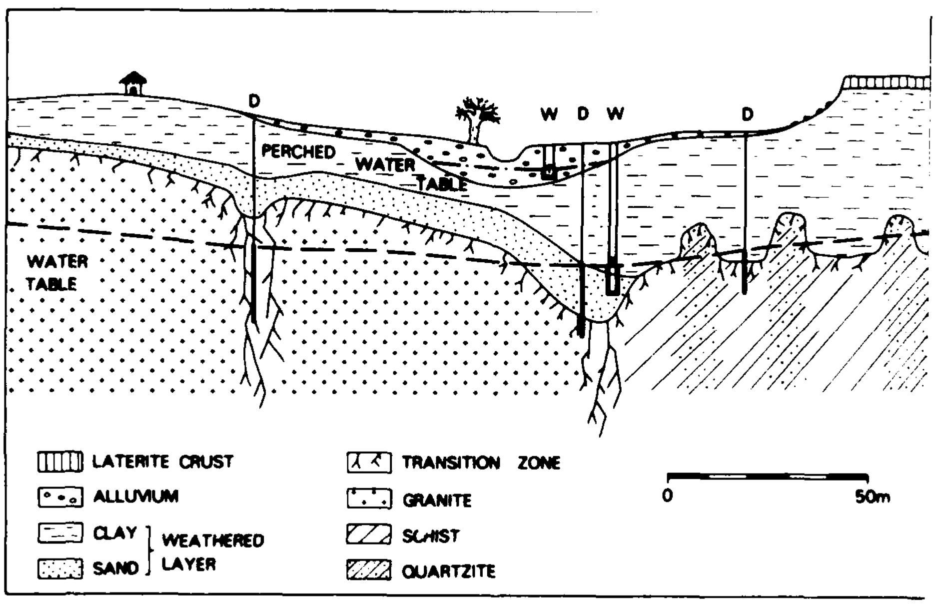


**Figure 4. Typical cross section of ground-water conditions in the Upper Volta region of western Africa**

stratigraphic indicators of ground water. In the upper part of the figure, a seasonal stream is shown; in Saudi Arabia, this could correspond to a wadi. During and after the rainy season, significant quantities of ground water can be present in the permeable sediments if they are underlain by relatively impermeable materials. Ground water occurring under the conditions shown here is referred to as a perched water table. Also, notice that there is a water table extending across the entire cross section at a greater depth. However, in locations where the water table is below the surface of relatively impermeable bedrock or basement rock, a well could produce little or no water.

In structurally controlled situations, such as the fracture zones, there is sufficient permeability to permit ground-water exploitation, provided that the fracture zone can be tapped. The depressions on top of the bedrock are also possible well locations where there are permeable sediments filling the depression below the water table. These depressions are sometimes structurally controlled, such as the ones associated with fracture zones or erosional features, such as ancient stream channels, or both. Another stratigraphic indicator would be the presence of permeable materials overlain by impermeable materials (possibly an aquiclude). Thus, there are both stratigraphic and structural indicators of the possible presence of ground water.

The classical geophysical approach to ground-water exploration involves one or more of three geophysical techniques: gravimetry, seismic refraction, and electrical resistivity. I will briefly describe the concepts behind these techniques, show pictures of some equipment, discuss limitations of the techniques, and present an adaptation of the geophysical approach to groundwater exploration. Generally, this classical geophysical methodology works quite well, but the questions that must be answered are:

a. Can the methodology be adapted for use by Army terrain teams in envisioned situations (e.g., hostile conditions)?

b. Will the inherent uncertainties in the procedures be acceptable?

c. Are there emerging geophysical technologies that promise more direct and positive ground-water assessments?

## Gravimetry

A small, lightweight, and portable gravity meter (Figure 5) is all that is needed to conduct a gravity survey. The battery will last for a 10-hr working day and can be recharged overnight. Although a survey crew is often

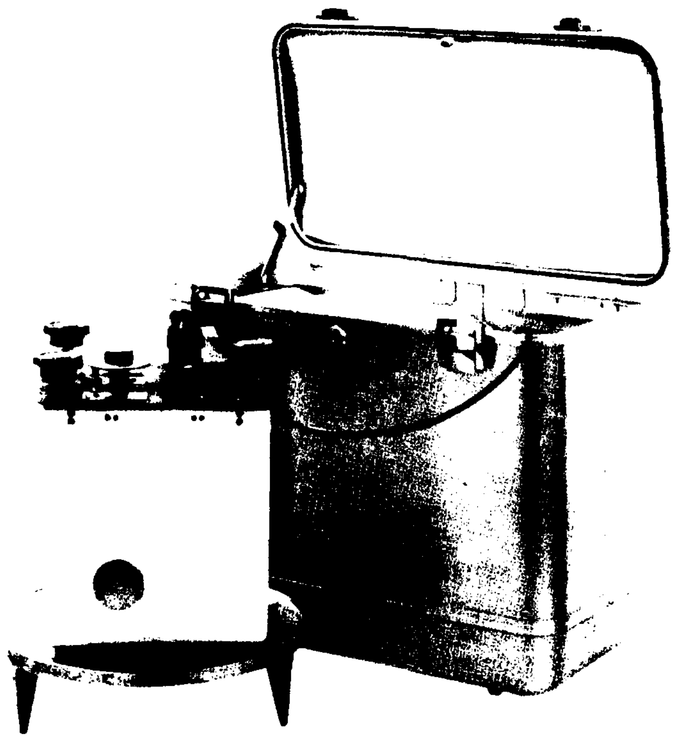

Figure 5. LaCoste & Romberg Model-D Gravimeter

needed to locate gravity stations and to determine elevations relative to some base station or benchmark, only two people are needed to conduct a gravity survey--one to read the meter and one to record the data. Technicians can be trained to make high-quality gravity meter readings. Three to five minutes are generally required to obtain a gravity reading at a station, and, depending on station, spacing, and terrain, as many as 50 gravity measurements can be obtained in a day. Basically, there are no logistical problems involved in gravity surveying.

Gravimetry is used in ground-water exploration to determine the structure of basement rock or bedrock (i.e., the topography of the top of bedrock). We are interested in locating areas having thicker accumulations of sediments than surrounding areas. Figure 6 is a gravity anomaly map, an example of the results of a gravity survey conducted in the Sudan. The dots are gravity stations, and gravity values for the stations are used to produce the contour map. To achieve these results, considerable data processing is required. The data manipulations are fairly routine and can be programmed for processing by a microcomputer. The gravity "lows" extending in a northwesterly direction

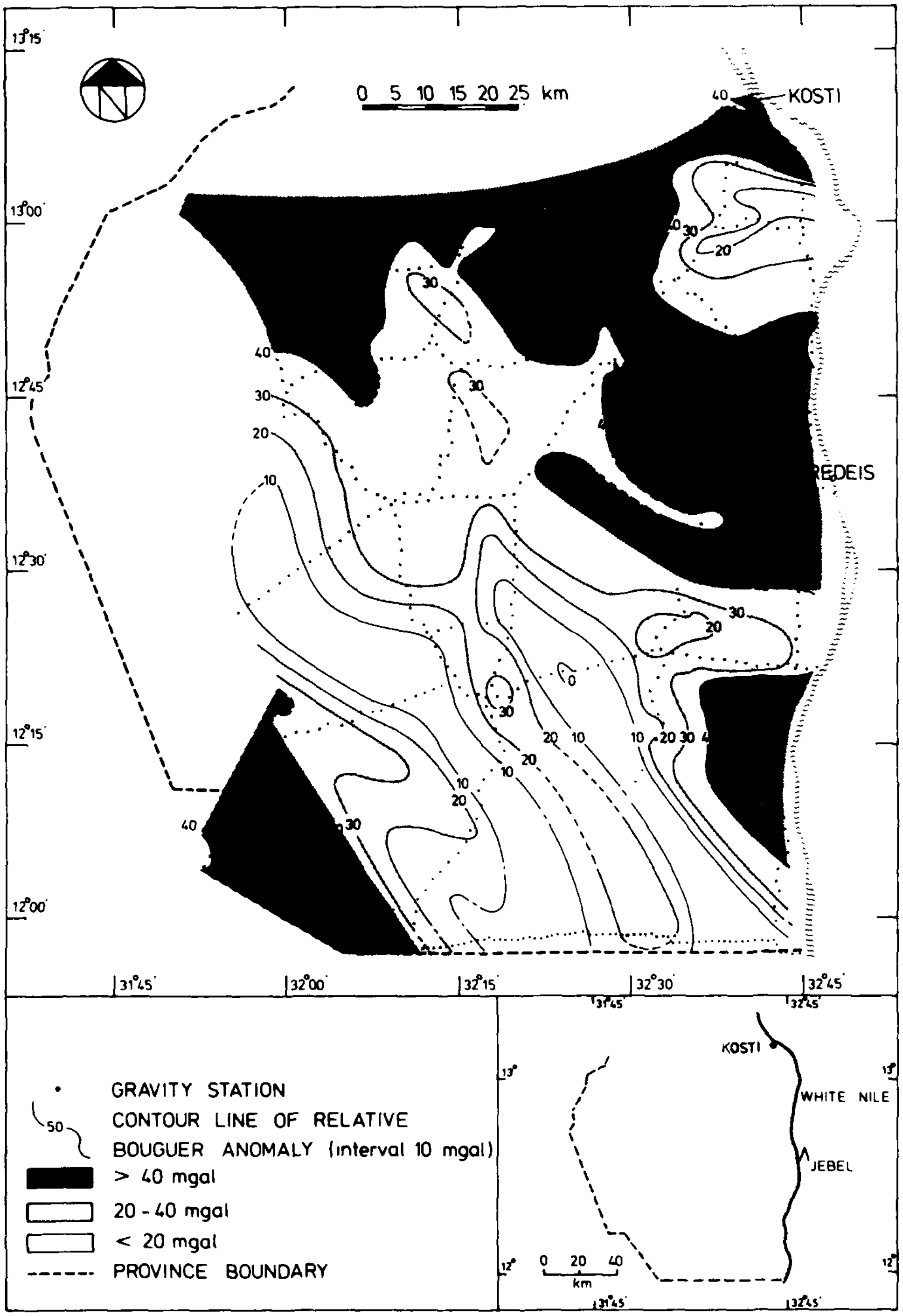


Figure 6. An example of the results of a gravity survey (Source: Van Overmeeren, R. A. 1981. "A Combination of Electrical Resistivity, Seismic Refraction, and Gravity Measurements from Ground-Water Exploration in the Sudan," Geophysics, Vol 46, No. 9 (Sep), pp 1304-1313)

are due to significant depressions in the top of rock, probably caused by down-faulted basement blocks. Localized basement depressions are also evident in the east-central and northeastern portions of the map. Such regional gravity maps can be used either for planning exploratory drilling or for more detailed geophysical surveys.

Conducting a gravity survey for ground-water exploration in a forward area is not always practical; however, engineer teams can sometimes survey along selected profile lines. Additionally, gravity maps, such as Figure 6, are available for portions of Southwest Asia and should be part of any geologic-geophysical database.

## Seismic Refraction

Figure 7 shows a 24-channel seismic refraction unit. In terms of equipment, all that is missing is a seismic energy source, such as an explosive charge or a large weight drop source, cable and reel, and 24 geophones (small surface sensors). This equipment is very portable and rugged. If the desired maximum depth of investigation is 1500 ft, a surface layout of three or four times that dimension (or about 1 mile) would be required.

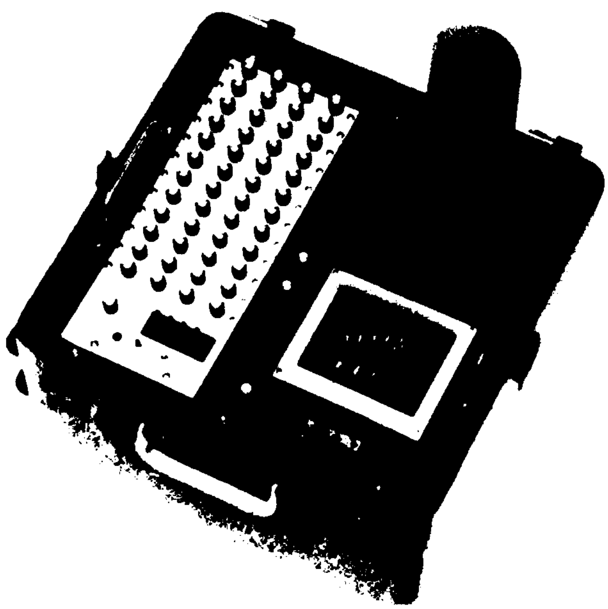

Figure 7. Twenty-four channel seismic refraction unit

Figure 8 illustrates the concept of seismic refraction. Geophones (seismic sensors) are placed on the surface along a line from a seismic energy source, with the objective being to detect energy that is refracted along interfaces between different geologic materials and then travels back to the ground surface. The seismograph record is analyzed, and a plot of first arrival times versus distance from the energy source is prepared (Figure 9). We interpret these data to determine seismic velocities and depths to interfaces. Although not completely unique, geologic materials can be characterized

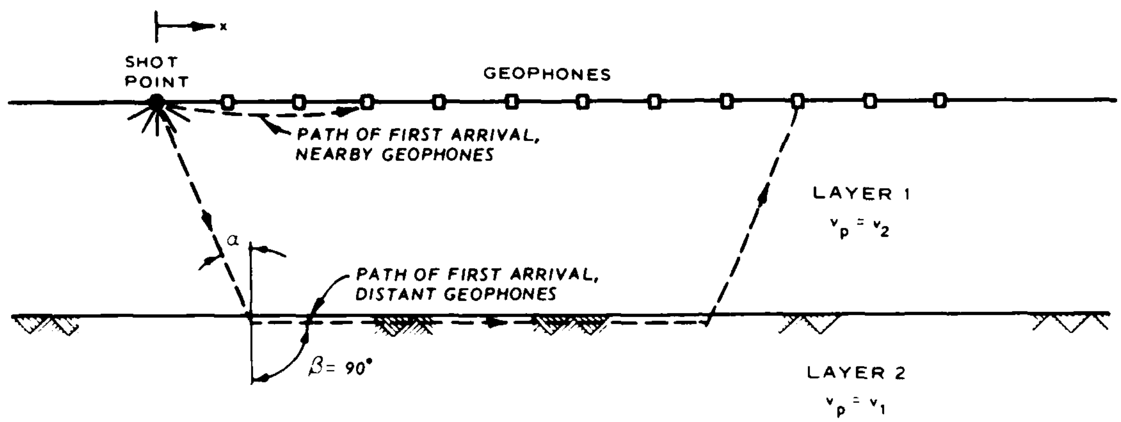


Figure 8. Schematic of seismic refraction survey

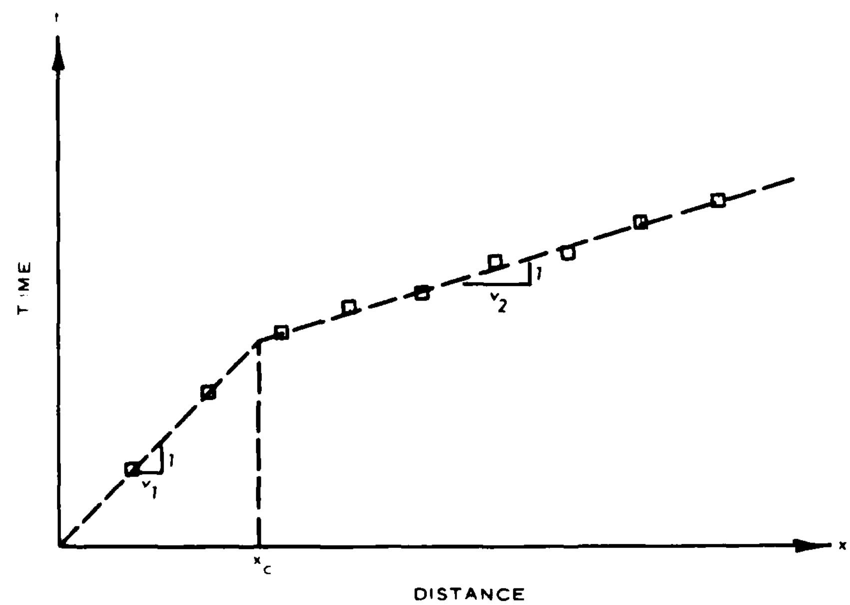


Figure 9. Time versus distance plot for seismic refraction survey (Figure 8)

by their seismic velocities. In unconsolidated sediments, the seismic velocities are lower than those characteristic of saturated sediments. Although other materials can have a similar velocity, when we encounter a 1500 m/sec velocity, and the known geologic conditions do not indicate that other such materials are likely to occur, we strongly suspect the presence of ground water.

Typically, a three- to four-man crew is desirable for seismic refraction surveying; however, logistics for this method are often more complicated than for gravity surveying. Although data processing can be accomplished with a hand-held calculator, subjective judgment is sometimes required for analyzing the seismograph records. Simple interpretation of seismic refraction data assumes that seismic velocities always increase with depth. Errors in calculated depths can result when velocity reversals (low velocity zones) occur.

## Electrical Resistivity

Electrical resistivity is the most versatile and most often used technique for ground-water exploration. Figure 10 shows a set of resistivity equipment items that we use for very shallow investigations (to a depth of about 100 ft). This equipment is very durable and portable. Equipment to conduct investigations to depths on the order of 1500 ft will, of course, be larger and sometimes requires a generator power source; much of the increase in size and weight, however, is due to the additional cable needed.

There are numerous ways we can arrange the four electrodes and conduct field surveys. The electrodes can be expanded symmetrically about a given surface point to produce a vertical sounding or maintained at a constant spacing and moved about to different locations, producing data on lateral variations. Generally, current is input to the ground with the two outer electrodes, and potential difference (voltage) is measured with the inner electrodes. A three- to five-man crew is required for resistivity surveying. Logistically, resistivity and seismic refraction are equally complicated.

Resistivity sounding data can be used to interpret resistivities and

Figure 10. Resistivity equipment used for very shallow investigations

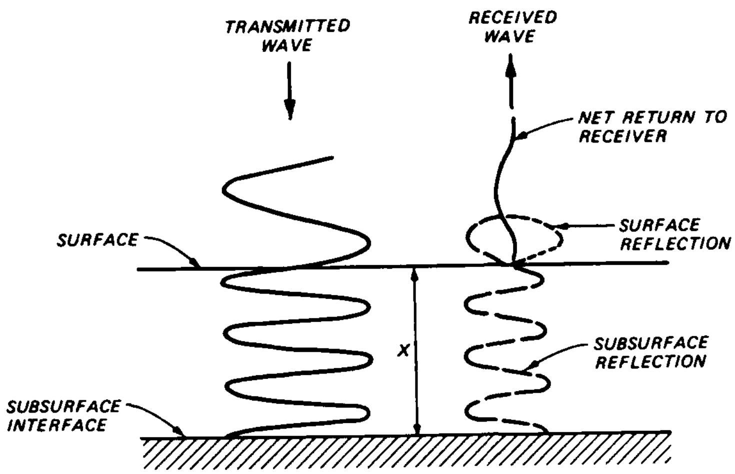


Figure 4. Wave phase change in soils

) have its own characteristic impedance as calculated by the equations below ,undien 1972b, 1978):

$$Z_{on} = \sqrt{\mu_n^*/\varepsilon_n^*} \tag{2}$$

$$\mu_n^* = \mu_o \mu_{rn}(1 - j \tan \delta_m) \tag{3}$$

$$\varepsilon_n^* = \varepsilon_n \varepsilon_{rn}(1 - j \tan \delta_d) \tag{4}$$

ıere

$Z_{on}$ = characteristic impedance for the $n^{th}$ layer, ohms

$\mu_n^*$ = complex magnetic permeability for $n^{th}$ layer, henrys/m

$\varepsilon_n^*$ = complex dielectric constant for $n^{th}$ layer, farads/m

$\mu_o$ = free-space magnetic permeability, henrys/m

$\mu_{rn}$ = relative magnetic permeability for the $n^{th}$ layer, dimensionless

$j = \sqrt{-1}$

$\tan \delta_m$ = magnetic loss tangent, dimensionless

$\varepsilon_o$ = free-space dielectric constant, farads/m

$\varepsilon_{rn}$ = relative dielectric constant for the $n^{th}$ layer, dimensionless

$\tan \delta_d$ = dielectric loss tangent, dimensionless

ıese impedances cause a change in the power reflection at the surface of the ıyered embankment as computed by the equations shown on the following page:

when $\sigma/\omega\varepsilon$ is greater than 1, the material is a conductor, and when $\sigma/\omega\varepsilon$ is less than 1, the material is dielectric. At high frequencies (i.e., above a few megahertz), most nonmetallic terrain materials act as dielectrics insofar as their reflecting properties are concerned and the dielectric loss tangent is relatively insensitive to frequency changes over small bandwidths. The waves transmitted through the surface into the material are, however, rapidly attenuated.

The measurements discussed in this paper were made at high frequencies (0.25 to 2.0 GHz) and, therefore, the materials are considered to be dielectrics or poor conductors. For these materials (especially low-loss materials), energy penetration is possible, and reflection from subsurface layers can combine with surface reflections to give a total amplitude highly dependent on the layer geometry and transmitter frequency. Thus, a measurement at a single frequency cannot be used to predict the surface reflectance unless the test site is known to be without layers.

In general, the reflectance from an unlayered test site will change with increasing frequency because of the decreasing conductivity effect. Thus, in some cases, electrical properties can be predicted by making measurements at two frequencies, one much lower than the other, and noting the change in measurement amplitudes. This approach is not possible for most field measurements because test sites usually have some degree of layering.

For layered test sites, subsurface reflection can combine with the surface reflection to produce a periodic amplitude change as the frequency is varied. This amplitude change is caused by destructive and constructive wave interference and decays with increasing depth. Figure 4 shows the transmitted and received wave geometry for destructive interference. In the case of field measurements, some scattering occurs from rough surfaces and in the transition zones between subsurface layers. This scattering reduces the influence of multiple-reflected waves. The net result, an increase in the noise level of the reflected signal, gives a somewhat random appearance to the reflectance curves.

To assist in the study of layered test sites, a theoretical model based on complex electrical impedances of the various dielectric and magnetic materials that made up the layered embankment was used a guide for determining the accuracy of the analysis procedures. Each layer in the embankment was assumed

purpose of this analysis, a thin transition zone is one whose thickness is less than one-eighth of a wavelength of the transmitted signal (Rayleigh criterion) (Lundien 1972a).

c. Each layer surface was smooth. Again, smoothness is a matter of degree and can be evaluated by comparing the surface roughness deviations to one-eighth of a wavelength of the transmitted signal in the same manner as that for the transition zones. This assumption allows prediction of surface electrical properties because roughness generally tends to reduce the signal level at the radar receiver by scattering the reflected energy and thus tends to decrease the accuracy of the computations.

d. The top and bottom surfaces of each layer were parallel to each other and perpendicular to the radar beam center line. If the boundaries between the layers were not parallel, the layer thickness would not be uniform. Additionally, a sloped surface would tend to direct the reflected energy away from the receiver and thus reduce the amplitude of that signal component.

The above assumptions do not restrict operation to only ideal test sites; rather, the accuracy of computed results is increased when the assumptions are met.

## Spectral Response

The reflectance of a material can be highly dependent on the frequency of the microwave source. Materials are roughly divided into two classes: (a) conductors and (b) dielectrics (or insulators). The dividing line between the two classes is not sharp, and some materials (soil, for example) are considered to be conductors in one part of the radio frequency range and dielectrics in another part. The criterion for classification is the value of the dielectric loss tangent ($\tan \delta_d$) defined by:

$$\tan \delta_d = \frac{\sigma}{\omega \epsilon} \qquad (1)^*$$

where

$\sigma$ = electrical conductivity, mhos/m

$\omega$ = circular frequency (= $2\pi f$), radians/sec

$\epsilon$ = dielectric constant, farads/m

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* $\sigma/\omega\epsilon$ is also defined as the ratio of conduction current density to displacement current density in the material.

systems (including pulsed radar systems) and to reconstruct the electrical profile of the test sites. Although the processing techniques and the examples presented in this paper were developed for frequency bands with limited depth of penetration to emphasize layer resolution in the top few metres of soil and pavement materials, the transmitter can be operated at lower frequencies to increase penetration depths to those practical for rapid ground-water surveys. Details of the reconstruction process, as appropriate for ground-water detection, are discussed in this paper.

## Target Model

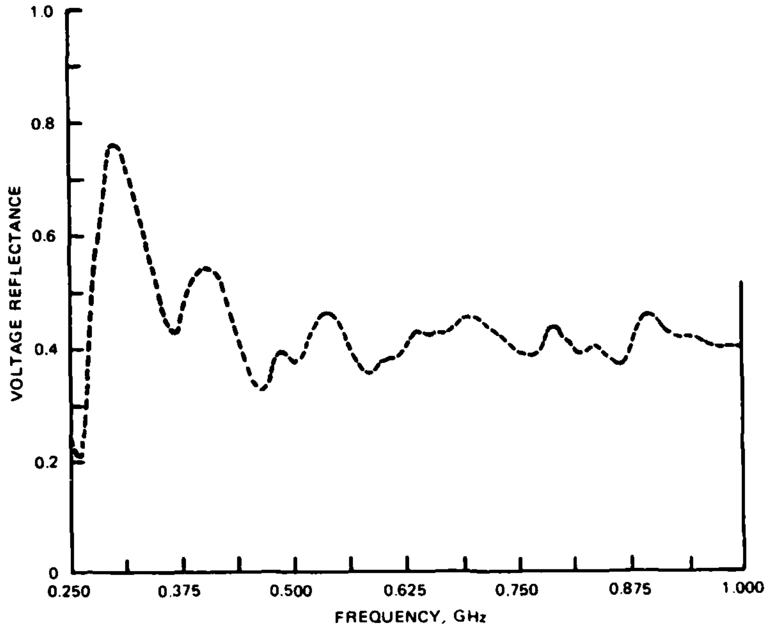
When an electromagnetic wave traveling in one medium impinges upon a second medium having different electrical properties, the wave generally will be partially transmitted and partially reflected. The transmitted wave is attenuated as it travels through the second medium and, upon encountering a third medium, experiences partial reflection and transmission again. Theoretically, this process can continue indefinitely. The reflected signals of interest are those that travel back to the surface with enough amplitude to significantly alter the total amplitude of the return signal. The amplitudes of the reflected signals are governed by the properties of the medium.

## Assumptions

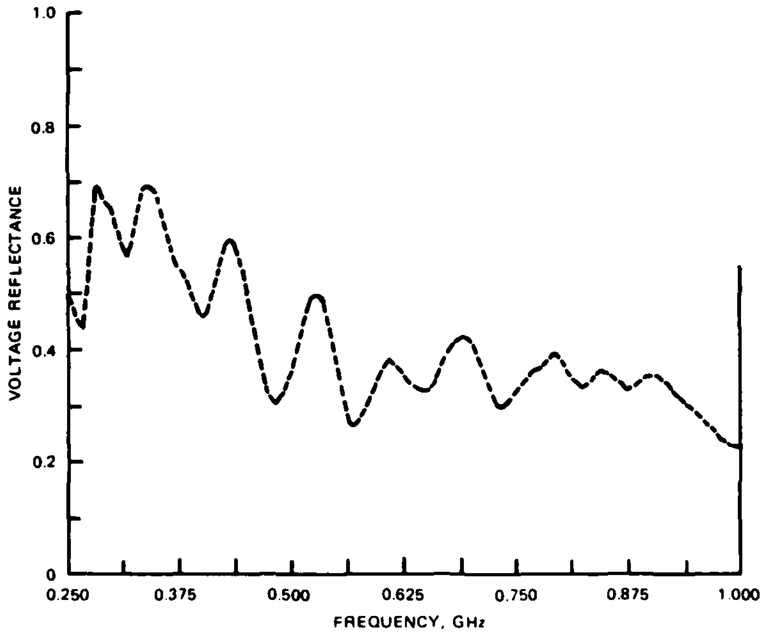
In using microwave systems certain assumptions regarding properties of a medium were made to simplify the methods used to extract information about the medium from the reflection curves. These assumptions are that:

a. The test sites were composed of layers of various thicknesses. The material in each layer was uniform and did not have any discontinuities either within the layer or at its top and bottom surfaces. The electrical properties of each material were assumed to be frequency independent (at least, over the frequency range used for calculations) and predictable from past tests in the laboratory.

b. The transition zones between the layers were very thin (negligible), and thus the layer interfaces were abrupt. A thick transition zone would tend to reduce the amplitude of the boundary reflection and could cause a layer to be overlooked. Transition zone thickness is a matter of degree because the thickness is measured relative to the wavelength of the transmitted signal in the material through which the wave is traveling. A thin transition zone at long wavelengths could be a very thick transition zone at short wavelengths. For the




a. Position one




b. Position two

Figure 3. Reflectance measurements for the sand soil site (Lundien 1981)

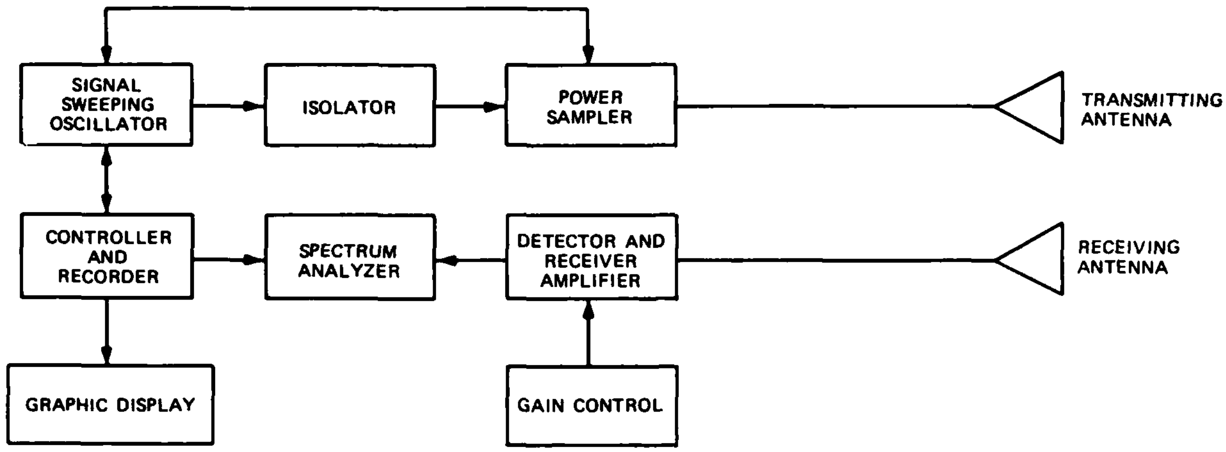



Figure 1. Simplified block diagram for a swept-frequency radar system

and then route them back to the control unit for formatting and further processing, recording, and display.

Soil measurements normalized by power incident on the ground surface define the power reflectance record. A voltage reflectance record is the square root of each measurement in the power reflectance record. Figures 2 and 3 are examples of the reflectance record from a highway embankment and a sand soil site, respectively. These records contain all the information necessary to synthesize the response from a variety of radar measurement

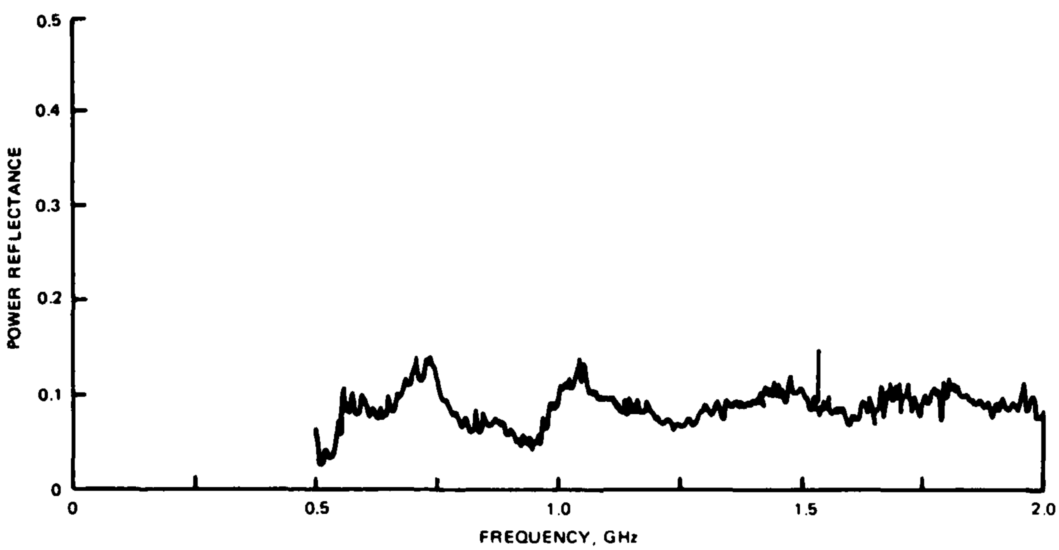



Figure 2. Radar signal from highway embankment (asphalt pavement, clay gravel base, silt substrate) (Lundien, 1972a)

# GROUND-WATER DETECTION: RADAR MEASUREMENTS OF SOIL ELECTRICAL PROPERTIES

by

Jerry R. Lundien*

## Introduction

Measurements with microwave systems have been conducted in the past at the USAE Waterways Experiment Station (WES) to document the electrical properties of soils over wide ranges of frequencies (Davis 1966; Lundien 1966, 1971, 1972a, 1981). The results of such measurements generally indicate that soil electrical properties are directly related to the physical properties and the natural physical state of the soil. In particular, the response of a soil at one state of moisture content and density can vary if the soil layer thickness is not uniform. Under certain conditions, these relations can be exploited to detect and establish the depth to a water-bearing layer, and to determine the relative quality of the water.

One device that can be used to measure electrical properties of soils and layer thicknesses is a swept-frequency radar system. A simplified block diagram of a swept-frequency radar is shown in Figure 1 (Lundien 1972a, 1981). The system is composed of two major subassemblies, the transmitter and receiving sections. The transmitter section consists of a signal oscillator, the output of which can be controlled in amplitude as the frequency is varied. A portion of the transmitted signal is sampled at the transmitting antenna and fed back to the signal oscillator to maintain constant transmitted power. Isolators are used between the signal oscillator and transmitting antenna to reduce interactions between components. The reflected waves from the ground surface and subsurface interfaces combine vectorially as they travel back to the receiving amplifier. The signal from the receiving antenna is then rectified by a crystal detector (which removes the radio frequency portion of the signal) and amplified in the receiver amplifier. Finally, the amplified signal is processed by the spectrum analyzer and controller to form a record. The spectrum analyzer can be used to average several sequential measurements, compute Fourier transforms of the received signal, and store records (i.e., the measured response over the frequency band of the transmitter) temporarily

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## Conclusions

A complementary application of seismic refraction and electrical resistivity methods at a site can be used to improve the assessment of ground-water prospects and to reduce the frequency of occurrence of dry holes in a drilling effort. The questions of equipment and field procedure modifications and of composition of engineer teams and training requirements necessary for the methodologies to be deployed under specified scenarios must still be addressed.

There are other geophysical techniques that have not been discussed. Some of these will be covered in the emerging technologies session. The seismic reflection and ground-penetrating radar (GPR) methods, often mentioned in discussions of ground-water exploration, are used to produce vertical reflection cross sections; thus, both methods can give only structural and stratigraphic indications of the possible presence of ground water. Like other interfaces, the water table acts as a reflector, and there is often nothing particularly diagnostic about the water table reflection event to distinguish it from all the other events on a seismic time section. Standard seismic reflection profiling is too cumbersome and logistically complex for application to military ground-water exploration. The GPR has a limited depth of penetration, and does not give any direct indication of the presence of ground water. Generally, current GPR systems are limited to depths of 50 ft or less; and even with equipment improvements, depths of investigation greater than 200 ft are very unlikely in the foreseeable future. Numerous other electromagnetic methods have potential applicability, but these techniques, such as induced polarization, magnetotelluric methods, induction methods, time-domain methods, etc., have not been used in systematic ground-water studies. The potential of these other methods to ground-water detection should be evaluated.

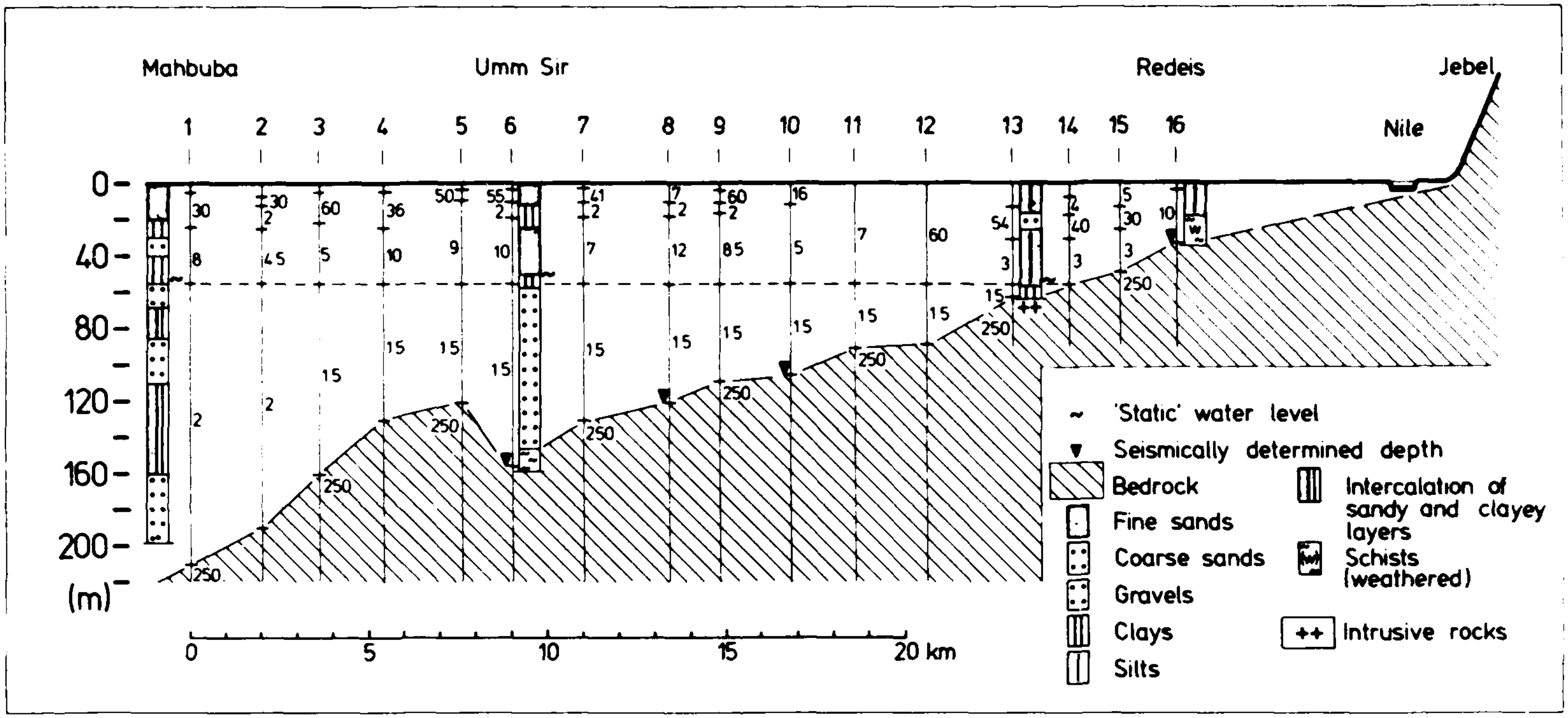



Figure 14. The final interpretation of the geoelectrical profile and the lithological columns of the boreholes. The test wells at VES 13 and 16 confirmed the geophysical results (Source: Van Overmeeren 1981)

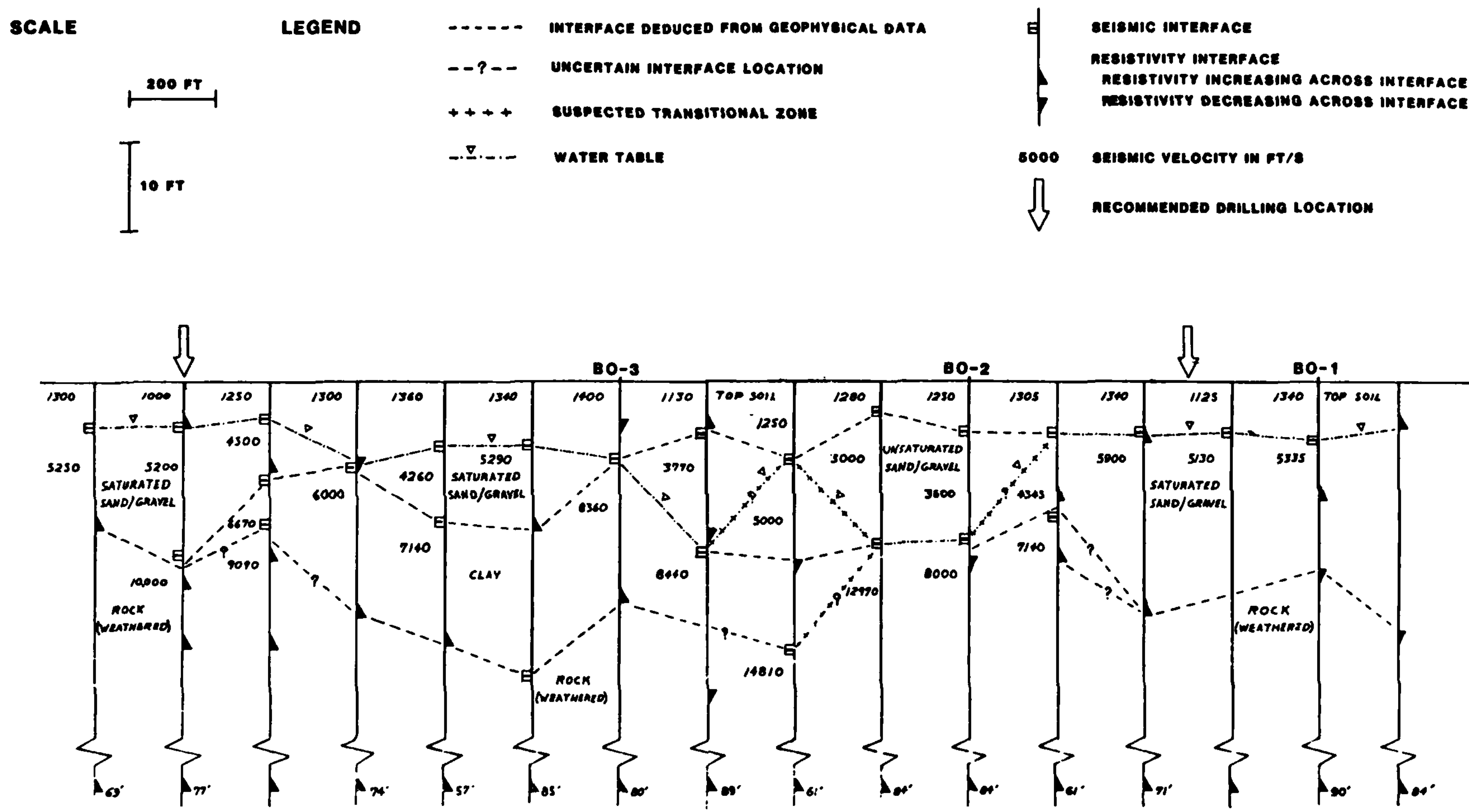



Figure 13. Osan AFB, Korea, geophysical cross section, runway-perimeter road area

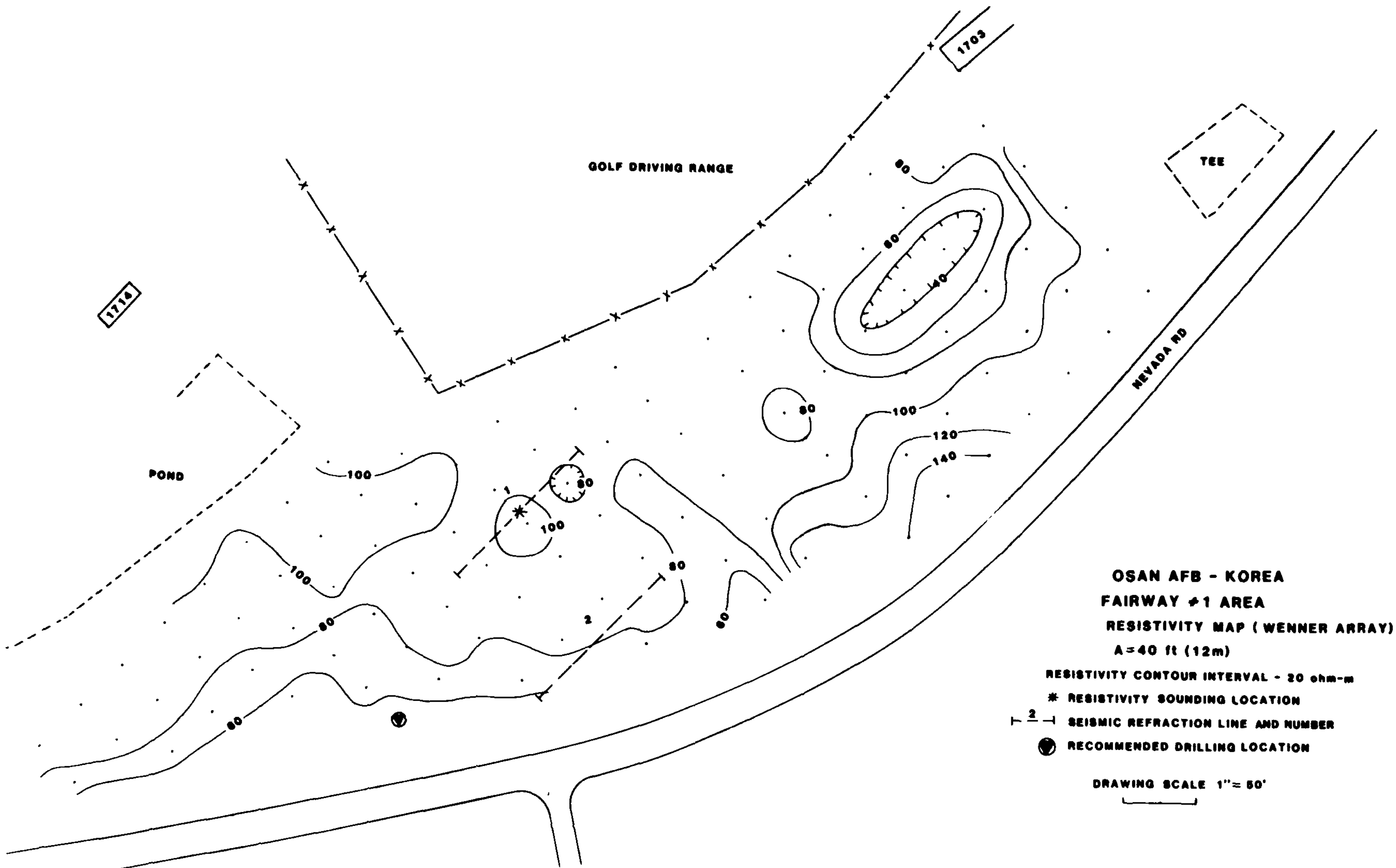



Figure 12. Resistivity contour map

Air Force Base, Korea, illustrates the use of complementary geophysical methods--seismic refraction and electrical resistivity. Figure 12 shows a resistivity contour map produced by using a constant spacing electrode array to obtain resistivity measurements on a grid over the area. Results of a seismic refraction survey and an electrical resistivity sounding in the center of the area served as the basis for selecting the electrode spacing to produce the resistivity map. The objective was to locate depressions in the top of rock, which could indicate greater thicknesses of permeable sediments. The closed resistivity low shown in this figure could be caused by a localized depression in the top of rock. A buried stream channel would show up as an elongated low resistivity area.

Figure 13, also from the Osan study, shows a geophysical cross section produced from seismic refraction surveys and electrical resistivity soundings at 200-ft intervals along a profile line. The water table was detected at shallow depths nearly everywhere along the profile line. Again, the objective was to find depressions in the top of rock. Although ground water occurs nearly everywhere on the base, in many cases either the demand exceeds the capacity of the well or the aquifer is locally pumped down after only a few years. The key fact that emerges from examining this cross section is that the aquifer is not laterally continuous over the base but is interrupted by clay bodies, as shown in Figure 13. The clay here could be filling a shallow erosion channel in the top of rock. Boring BO-3 verified the identification of the material in the zone as clay. Existence of the clay bodies throughout the base would explain the local aquifer depletion experienced.

Sudan

Earlier, we discussed a gravity map of a portion of the Sudan. This next figure (Figure 14) shows a geophysical cross section along a selected profile line. Sixteen resistivity soundings were conducted along the 30-km profile line. Two existing water wells and four seismic refraction surveys, conducted in conjunction with the gravity survey, provided additional control on the depth to the water table and top of rock. The results shown in the cross section were confirmed by two boreholes at sounding locations 13 and 16.

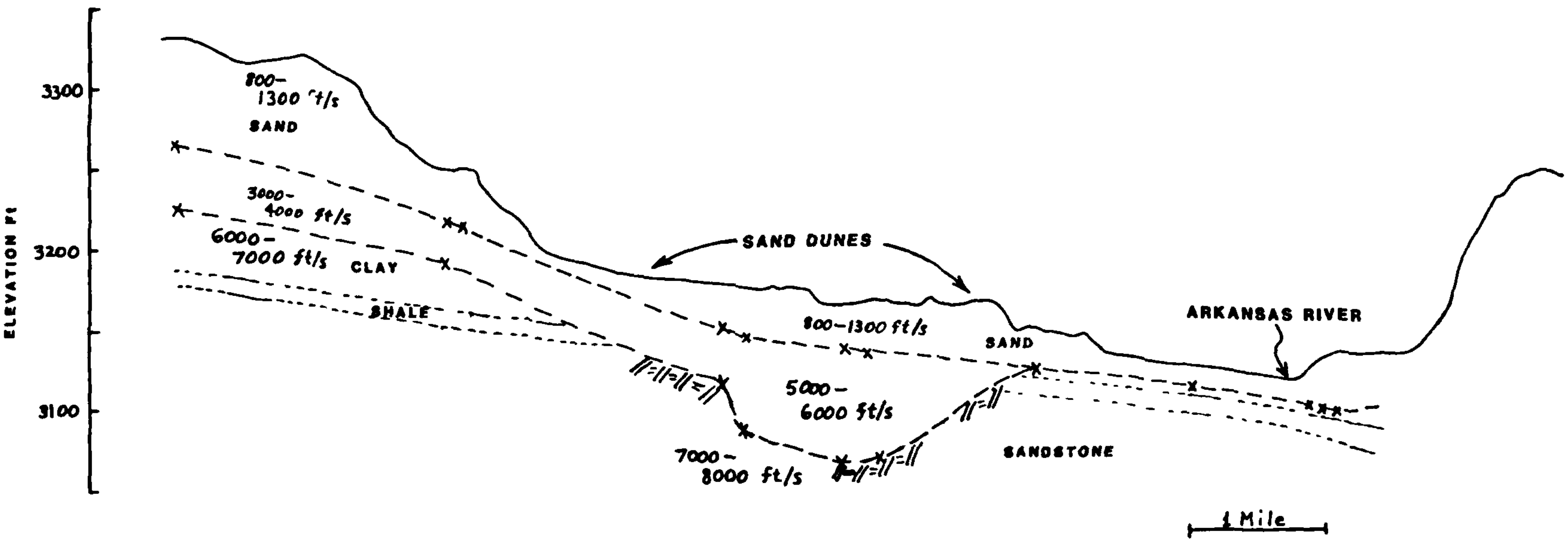



Figure 11. Buried channel delineated by seismic refraction in western Kansas

thicknesses of subsurface layers; however, such interpretations are nonunique because there are often numerous possible geologically reasonable interpretations of the data. We like to use a multiple-method approach, which includes consideration of supplementary data, such as well logs or the results of other geophysical techniques applied at the same locations, to aid in the interpretation of the resistivity data.

## Case Histories

### Saudi Arabia

About 7 years ago, we sent a team to Saudi Arabia to explore for well sites for base water supplies in two wadis. The exploration effort relied on one geophysical technique--seismic refraction. Several candidate sites were located and subsequently drilled, with several of the wells producing water. The main problem was determining (without supplementary information) if the characteristic 1500 m/sec velocity was due to a water table and not to a weathered rock or a clay layer. Electrical resistivity surveys conducted in conjuction with the seismic refraction would have helped reduce the uncertainty.

### Western Kansas

The next example (Figure 11) is a cross section from a seismic refraction survey at a proposed damsite in western Kansas. Again, only one geophysical technique was utilized. You can see the present location of the Arkansas River, which is subject to large seasonal fluctuations at this location (i.e., the flow is very low during most of the year). The area is semiarid (with sand dunes covering the surface). The interesting feature in the cross section is an apparent buried stream channel filled with saturated sediments. This channel has been defined solely from the geophysical data; however, boreholes near each end of the profile provided geologic control for construction of the cross section. The water table over the buried channel has been inferred to be at the depth where the seismic velocity increases from a range of 250 to 400 m/sec to a range of 1500 to 1800 m/sec. Therefore, the cross section suggests that there is a significant thickness of saturated sediments at the location of the buried stream channel.

### Korea

The next case history, which involves exploration for well sites at Osan

$$R = \left|(Z_{L1} - Z_{air})/(Z_{L1} + Z_{air})\right|^2 \tag{5}$$

where

$$Z_{Ln} = Z_{on}\left\{\left[Z_{Ln+1}\cosh(\gamma_n \ell_n) + Z_{on}\sinh(\gamma_n \ell_n)\right] \Big/ \left[Z_{on}\cosh(\gamma_n \ell_n) + Z_{Ln+1}\sinh(\gamma_n \ell_n)\right]\right\} \tag{6}$$

$$\gamma_n = j\omega\sqrt{\varepsilon_n^* \mu_n^*} \tag{7}$$

and

$R$ = power reflectance

$Z_{air}$ = characteristic impedance for air (377 ohms)

$Z_{Ln}$ = load impedance for $n^{th}$ layer, ohms

$\gamma$ = propagation factor, ($\gamma = \alpha + j\beta$) $m^{-1}$

$\ell$ = layer thickness, m

$\omega$ = angular frequency, radians/sec

$\alpha$ = attenuation constant, $m^{-1}$

$\beta$ = phase constant, $m^{-1}$

The attenuation constant $\alpha$ is equal to the real part of the propagation factor:

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1 + \tan^2\delta} - 1\right)} \tag{8}$$

The phase constant $\beta$ is equal to the imaginary part of the propagation factor:

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1 + \tan^2\delta} + 1\right)} \tag{9}$$

For wave propagation in low-loss and nonmagnetic media, $\tan^2\delta << 1$,

$$\sqrt{1 + \tan^2\delta} \approx 1 + \frac{\tan^2\delta}{2} \tag{10}$$

and

$$\alpha \approx \frac{\omega \tan \delta}{2c}\sqrt{\varepsilon_r} \tag{11}$$

$$\beta \approx \frac{\omega}{c}\sqrt{\varepsilon_r} \tag{12}$$

A computer program was written to calculate the power reflection as a function of frequency for the frequency range over which the radar system operates. Figure 5 is a condensed flowchart for this program. In the first

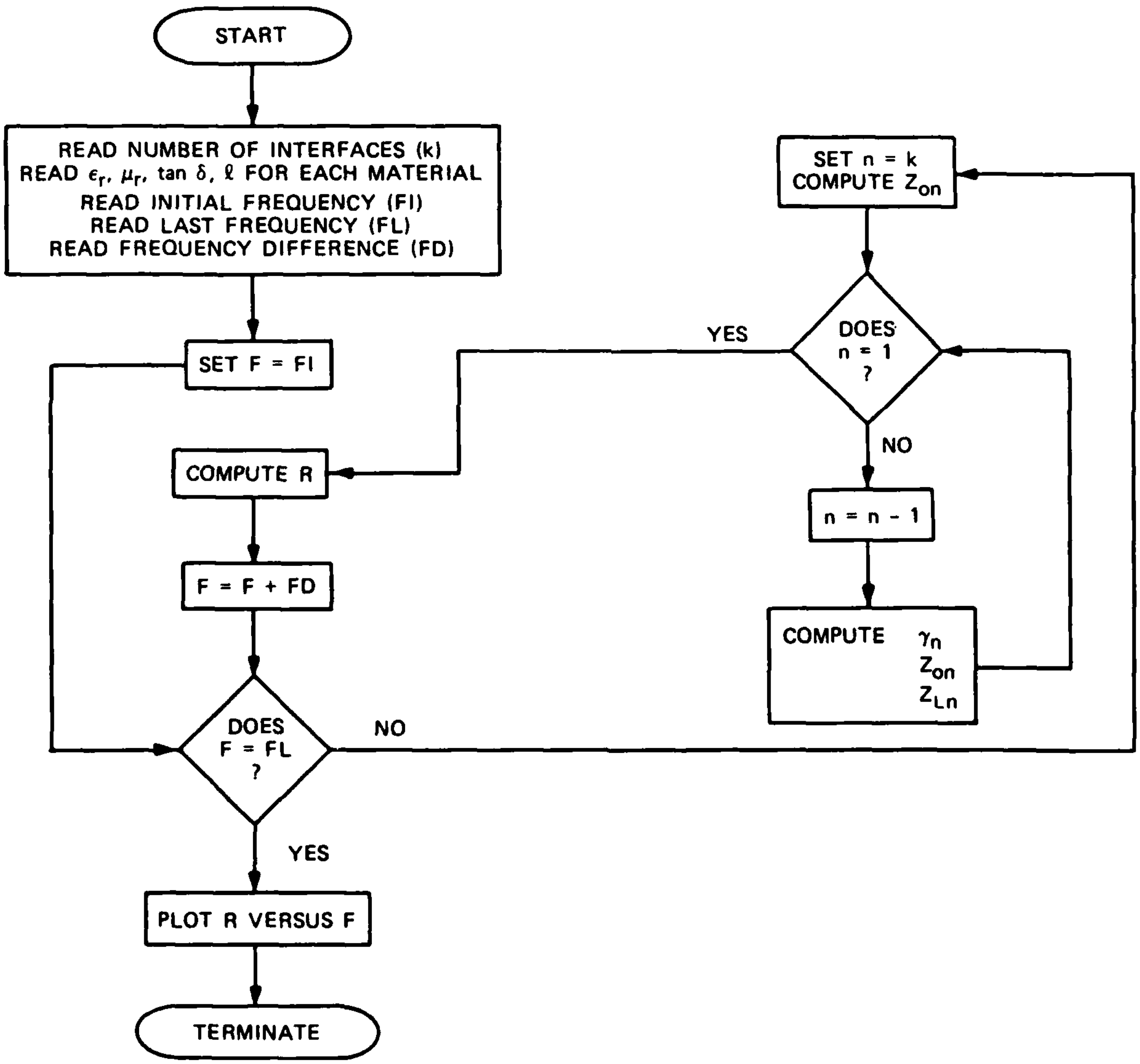



Figure 5. Condensed flowchart for radar reflectance program

step for this computer program, all the input data for each layer are defined along with the controls for radar operation. The program calculates impedances at each interface, starting at the lowest frequency and for the deepest material. The program cycles up through each layer, transforming impedances as it goes until it reaches the surface. At that point, a power reflectance is calculated and the next frequency is selected. The operation continues until all the frequencies have been exhausted.

## Spectral Analysis

The spectral analysis procedure was based on the detection of interference patterns in the power reflectance curves; the optical depth, defined as the distance between reflecting surfaces which if present in free space would produce interference patterns of the same period as in the layered medium, was computed as shown below:

$$\text{Optical Depth} = \frac{c}{2T_f} \tag{13}$$

where

$c$ = free-space wave velocity, $300 \times 10^6$ m/sec

$T_f$ = period between adjacent maxima or minima on interference pattern, Hz

Optical depth, in turn, can be converted to true depth by correcting for the wave velocity in the medium. For relatively low-loss materials, the decrease in wave velocity over free-space velocity can be approximated by the square root of the relative dielectric constant. The interference pattern period can be determined manually by measuring the frequency difference between interference maxima or interference minima from the reflectance curves and computing optical depth or by using more sophisticated signal processing techniques to extract the cyclic pattern information automatically.

A Fourier transform (the method used for this study) can be used to extract the cyclic pattern in power reflectance signal data. For this method, the mean reflectance is subtracted from each voltage reflectance data point; the results are transformed by a window function, and the data are then passed through a Fourier transform program. The window function used in processing data for this study was the minimum three-term Blackman-Harris Window (Harris

1978). Its purpose was to reduce the sidelobe content in the optical depth display. In the optical depth display, the locations of the peaks indicate the interface depths as detected by the swept-frequency radar system. A large peak would indicate a large interface reflection, while a small peak, a correspondingly small interface reflection. Because of distortions that can arise from the reflection of radar signals at complex boundaries, there can be both false peaks and real peaks in the optical depth display. The radar results were evaluated by establishing the real peaks marking interface reflections as being larger than the false peaks caused by the distortion of some of the interface reflections.

The Fourier transform program can be interpreted as approximating the results that could be obtained from a short pulse radar system. The windowing function serves to modulate the reflectance data in a pattern such that when the data are transformed to the time domain, a reflectance, delayed in time at each interface boundary, is obtained. Other radar systems can be simulated by using the same processing procedure and different processing windows. Thus, the basic site information is contained within the spectral record; a single measured time domain record contains the same information but usually with a large amount of processing noise.

<u>General analysis procedures</u>

A simplified flow diagram (Lundien 1981) for the general analysis procedure is presented in Figure 6. The objective of the analysis procedure is to adjust the input parameters to the theoretical radar reflectance model until the predicted radar reflectance curve matches the measured reflectance curve as closely as possible. The steps in the analysis procedure are presented in Figure 6.

The first two steps in the analysis procedure set up the theoretical radar reflectance model for computing reflectance over the frequency range of the measured data using the first and the second layers only (the second layer thickness is infinite), so that any echoes or false peaks in the optical depth display that show up at a depth greater than that of the first layer could be easily identified for later removal from consideration (step 4).

Once the layer properties for the first two layers have been input to the model, the power reflectance curve and the optical depth curve are computed (step 3). First, estimates for these layer properties are obtained from the measured data using layer reflectance and attenuation rate values. The

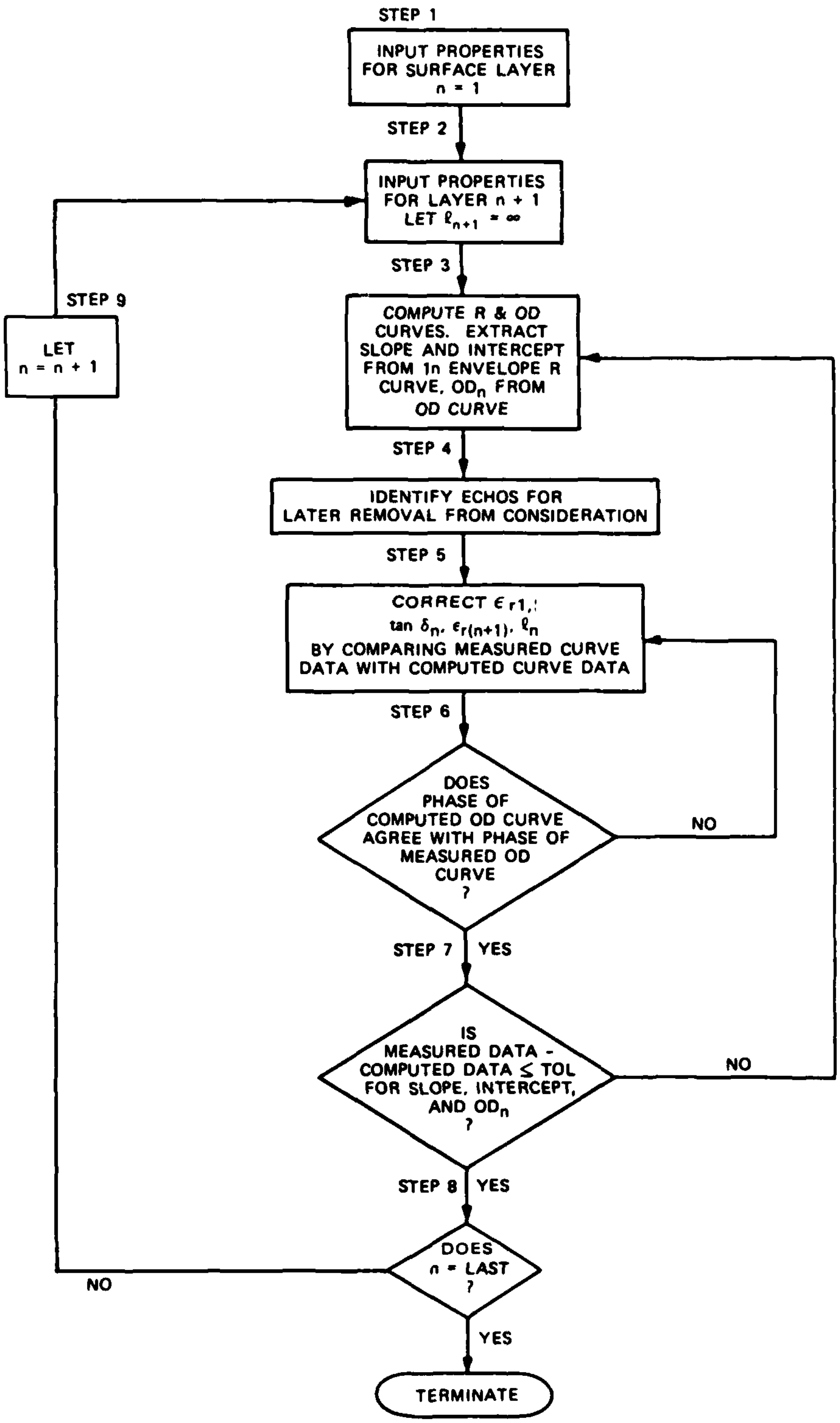



Figure 6. Flow diagram for the general analysis procedure (Lundien 1981)

interface voltage in the optical depth is isolated, the inverse Fourier transform is computed on the isolated peak (all other frequency components are zeroed), and the effects on the processing window are removed by normalizing. The linear slope and the intercept at zero frequency are computed from the natural logarithm of the envelope amplitude and the period is computed from the oscillating interface signal.

In step 5, corrections are made to the first estimates of layer properties by comparing computed values for the slope, intercept, and period from the model predictions with those from the measured data.

Checks are then made in step 6 to ensure the proper phase of the periodic interface data (this dictates whether the impedance contrast should increase or decrease at the next layer). Additional checks are made in step 7 to determine degree of fit between measured and predicted data. If any check is negative, another cycle is required to correct deficiencies.

When checks in steps 7 and 8 are positive, another layer is added (step 9) and the process is repeated. The process is terminated when all layers have been tested.

### Method for first estimate of layer values

As discussed previously, the method of processing data measured by the swept-frequency radar system made use of the Fourier transform and windowing functions to isolate the interference pattern for each interface. This considerably reduces the complexity of the problem from one of solving a matrix of simultaneous equations for all the layers to that of solving one set of equations for each layer separately. This solution is not free from problems, however. Because the process is sensitive to overlap between peaks in the time domain, and thus, in complex media, large computational errors result when the interface reflections cannot be cleanly separated.

Using a linear regression curve-fitting process and adjusting the results for overburden losses, the layer reflectance and attenuation rate can be computed. These values, in turn, together with the optical depth, are used to determine the relative dielectric constant $\varepsilon_r$, the loss tangent $\tan\delta$, and layer thickness $\ell$. Using $\varepsilon_r$ and $\tan\delta$, estimates can be made for the layer water content and material type. The details of this process are presented in a series of steps as shown below to illustrate the process.

In step 1 (computer program: Ratio) the measured data for power reflectance are placed in a file, and the square root of each data point is computed to obtain a signal proportional to the voltage reflectance. The average voltage reflectance is computed and subtracted from each data point. The average voltage reflectance is used to compute a first estimate of the surface $\epsilon_r$ .

In step 2 (computer program: Layer Filter), the results from step 1 are processed through a three-term Blackman-Harris Window of the form:

$$W(n) = a_0 - a_1 \cos\left(\frac{2\pi}{N} n\right) + a_2 \cos\left(\frac{2\pi}{N} 2n\right) \tag{14}$$

The time domain signal is obtained (optical depth display) by taking a Fourier transform of the data. Each interface reflectance signal is isolated by generating a new file that is filled with zeros, except for points where the peak occurs. The data are transformed back to the frequency domain with the inverse Fourier transform, and the windowing effects are removed by dividing each data point by the same Blackman-Harris Window applied earlier.

In step 3 (computer program: Envelope-Slope), the maximum and minimum points are found to define the envelope shape for each interface signal, the natural logarithm is computed for the envelope points, and a linear regression curve is computed to obtain the curve slope and intercept at zero frequency.

In step 4 (computer program: Layer Properties (A)), the interface reflection is computed from the following equation (see Figure 7):

$$Rn = \left(e^{b_n - b_{n-1}}{}^2\right)\left(\frac{Rn-1}{T^2_{n-1}}\right) \tag{15}$$

$$= e^{2b_n}\left(\frac{1}{T_1^2 T_2^2 \ldots T_{n-1}^2}\right) \tag{16}$$

and

$$\epsilon_{rn} = \epsilon_{r(n-1)} \left(\frac{1 + \sqrt{R_n}}{1 - \sqrt{R_n}}\right)^2 \tag{17}$$

where

$R_n$ = power reflectance for the $n^{th}$ layer, $(R + T = 1)$

$T_n$ = power transmittance for $n^{th}$ layer

b = intercept value from step 3

e = base of natural logarithm

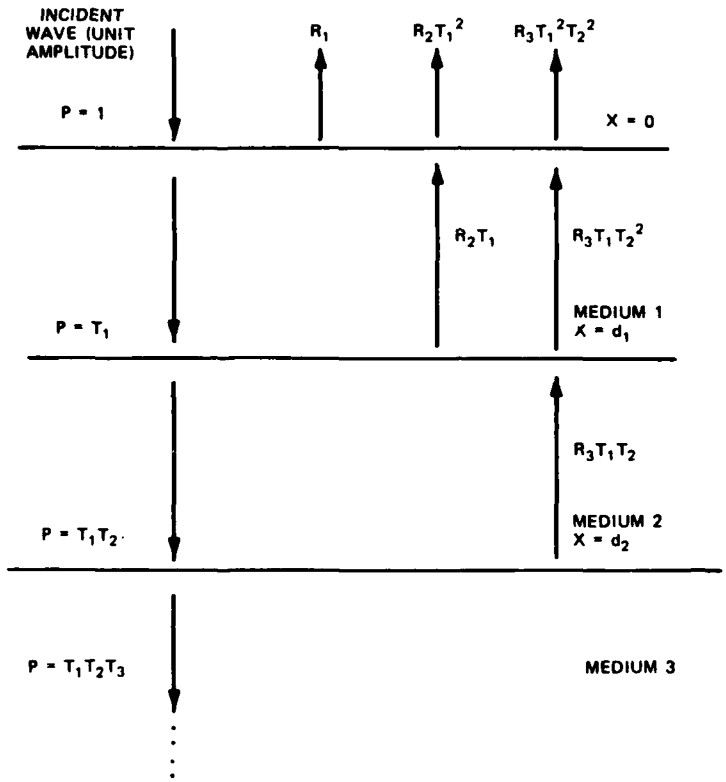



Figure 7. Power reflectance, R , and transmittance, T , for plane waves at normal incidence on plane sheets (layer attenuation is assumed to be negligible)

The total attenuation ($2\alpha\ell$) for a wave traveling round trip through a layer of thickness $\ell$ is computed as follows:

$$2\alpha\ell = 2\ell\omega\sqrt{\frac{\mu\epsilon}{2}\left(\sqrt{1 + \tan^2\delta_n} - 1\right)} \qquad (18)$$

and

$$-2\alpha\ell = (m_n - m_{n-1})\ f \qquad (19)$$

or

$$\tan \delta_n = \left\{ \left[ \left( \frac{2}{\varepsilon_r} m_{n-1} - m_n \right)^2 \left( \frac{C}{4\pi \ell} \right)^2 + 1 \right]^2 - 1 \right\}^{1/2} \tag{20}$$

where $m_n$ = slope of the $n^{th}$ layer from step 3. The layer thickness is computed from the optical thickness $\ell_o$ as follows:

$$\ell = \ell_o \sqrt{\varepsilon_r} \tag{21}$$

Estimates for volumetric water content (VWC) can be made using $\varepsilon_r$ and the results shown in Figure 8 or by using the following equation:

$$\mathrm{VWC} = \frac{\varepsilon_r}{80} - \frac{0.26}{\varepsilon_{r-1}} + 0.11 \tag{22}$$

A summary of loss tangent values for sand, silt, and clay soils is presented in Figure 9.

Two examples were selected to illustrate typical results from the general analysis procedure. The first example was taken from field tests on asphaltic concrete pavement structures (i.e., asphalt highway embankment) with a swept-frequency radar system (Lundien 1972a). The interstate highway was constructed on a silt foundation and at the time of the test had a 21.7-cm-thick asphaltic concrete surface. The pavement was separated from the silt foundation by a clay gravel base course. The moisture content and dry density during construction was 4.5 percent by dry soil weight and 1.94 g/cm$^3$, respectively, for the clay gravel base and 18.0 percent by dry soil weight and 1.58 g/cm$^3$, respectively, for the silt foundation.* Moisture content variations were noted as approximately $\pm$0.12 g/cm$^3$. The reflectance curve over the frequency range of 0.5 to 2.0 GHz is shown in Figure 2.

The second example was taken from tests on a sand soil site (Lundien 1981). Position one at the sand soil site was undisturbed soil, and position two contained an artificial interface (a buried aluminum sheet at a depth of 0.60 m). Positions one and two were directly adjacent to each other so that direct comparisons could be made of the measurement results. The surface soil was a fine sand with a moisture content of 6.0 percent by dry soil weight and

* The average moisture content of the clay gravel base material (measured shortly after radar measurements were made) was 7.2 percent.

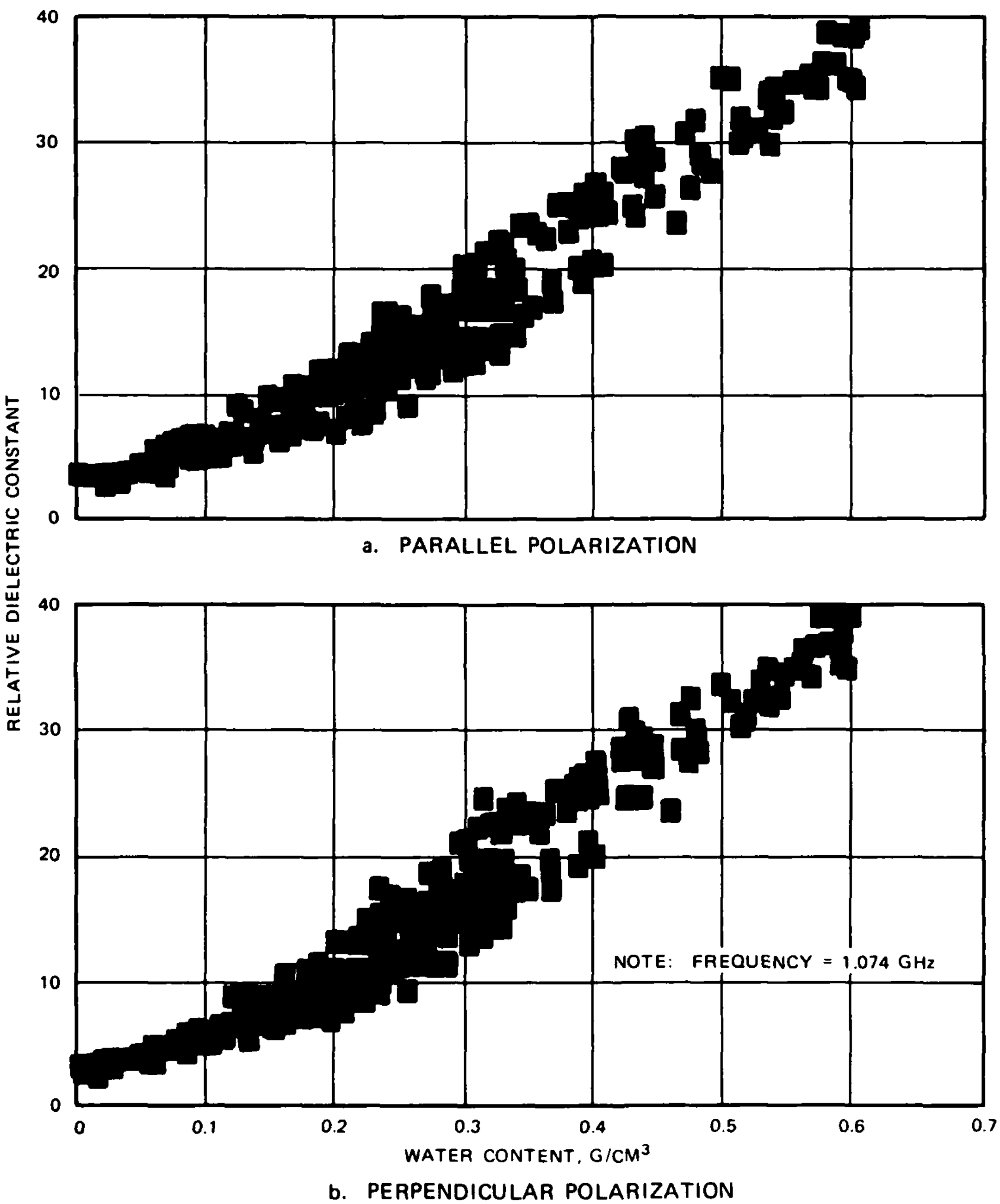
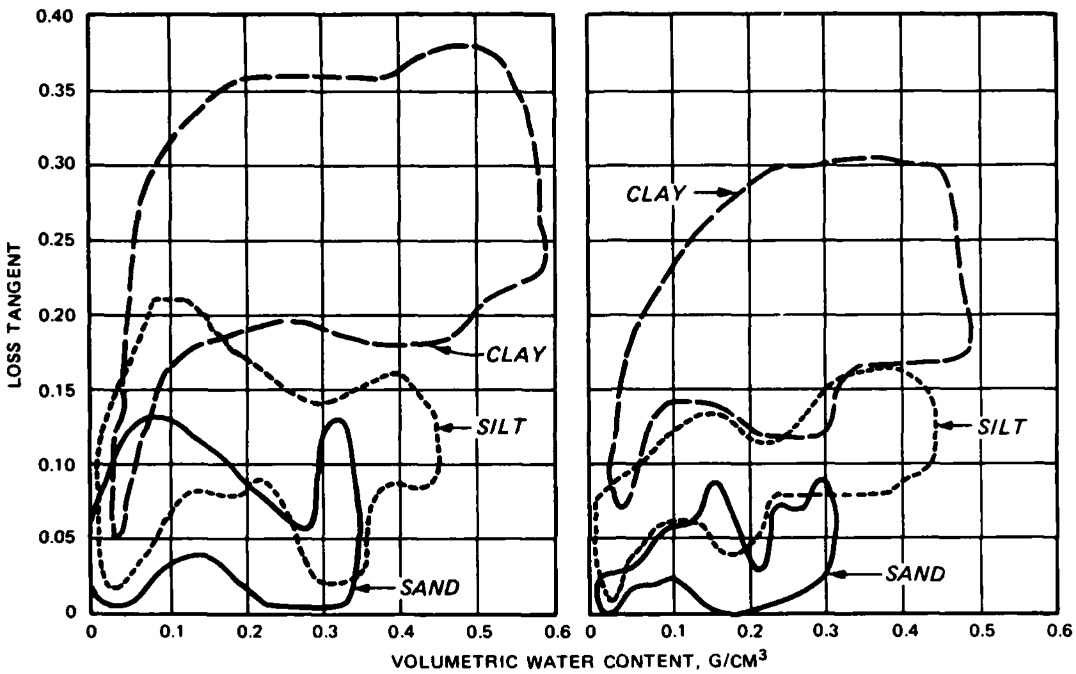



Figure 8. Effect of water content on relative dielectric constant (sand, silt, and clay soils) (Lundien 1971)




a. LOSS TANGENT, 1.074 GHz, ALL SOILS

b. LOSS TANGENT, 1.412 GHz, OKLAHOMA SOILS

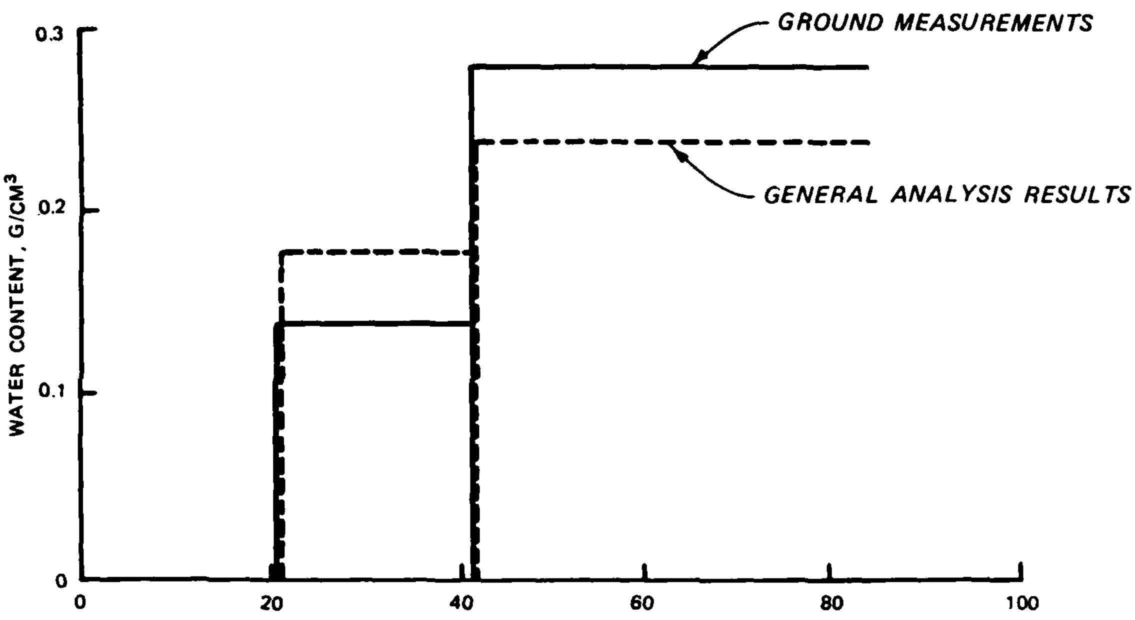
Figure 9. Summary of loss tangent for parallel and perpendicular polarization (Lundien 1974)

a dry density of approximately 1.6 g/cm$^3$. The reflectance curve over the frequency range of 0.25 to 1.0 GHz is shown in Figure 3.

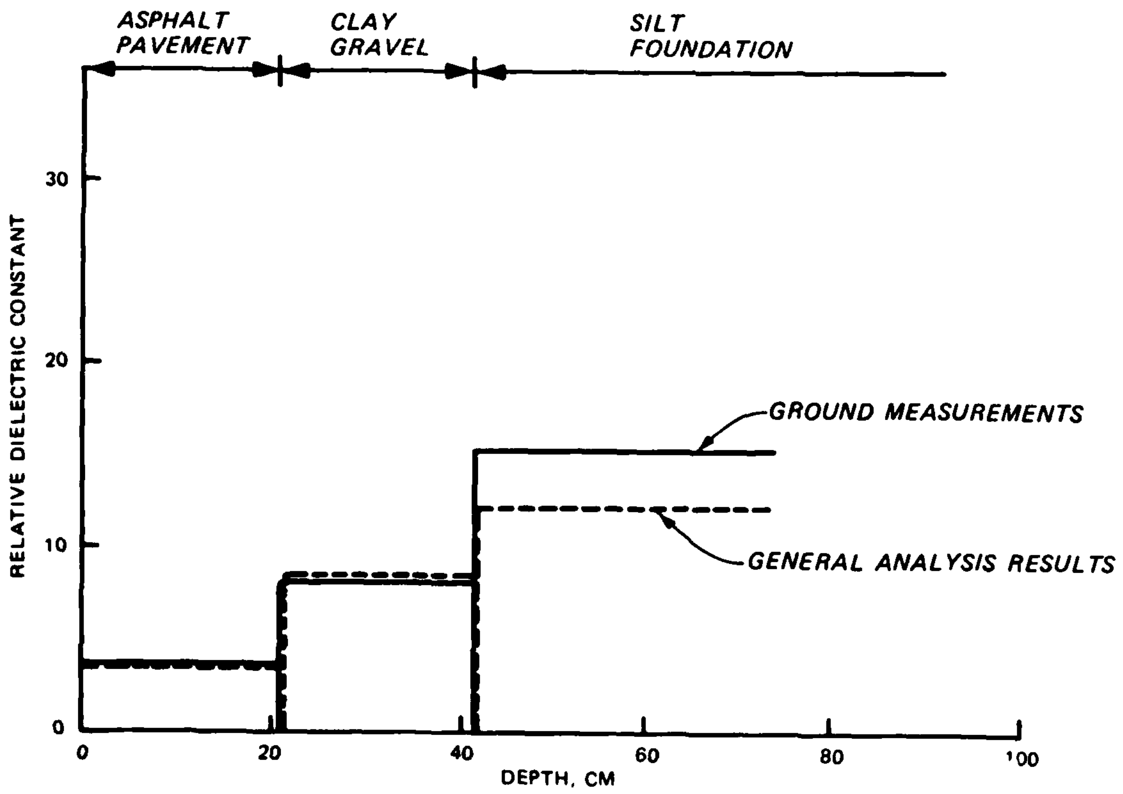
The results for these two examples are presented in Table 1. Figure 10 shows the relative dielectric constant and water content results for example 1 as determined from the radar measurements and ground measurements, respectively. (The relative dielectric measurements were estimated from the water content values.) Figure 11 provides good correlation of the power reflectance and relative dielectric constant results for example 2 at positions 1 and 2. Both examples indicate that noncontact measurements of ground properties can be made quickly and easily with specially constructed microwave systems.

## Summary

Radar systems offer distinct advantages over many sensing techniques because of their ability to make rapid, noncontact, nondestructive measurements that are sensitive to a changing electrical profile. When modeled as a layered media, the natural terrain fits many of the requirements desirable for

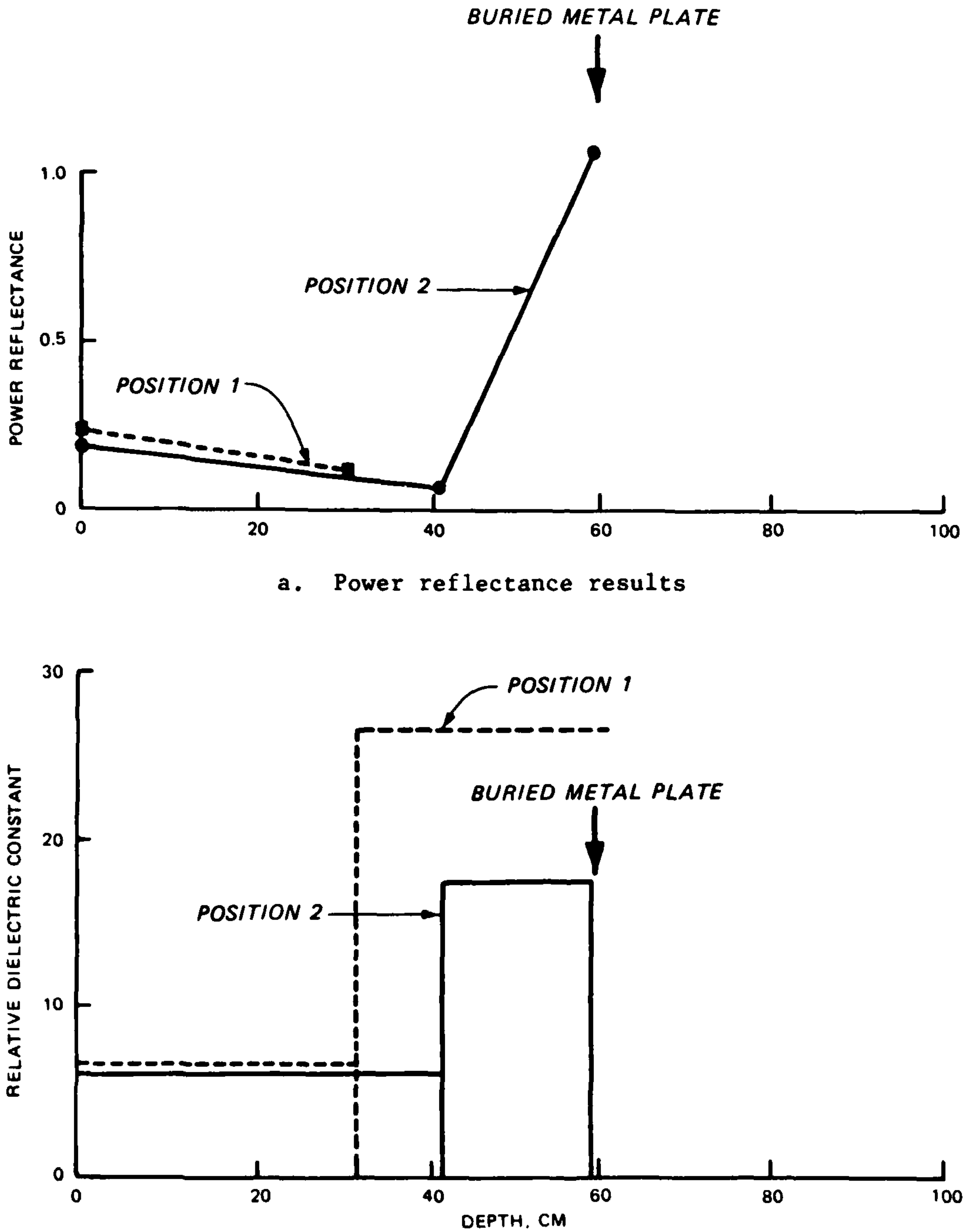



a. Water content results




b. Relative dielectric constant results

Figure 10. Results of radar tests for Example 1




a. Power reflectance results



b. Relative dielectric constant results

Figure 11. Results of radar tests for Example 2

:urate determination of the state of the ground using specially processed iar data. For ground-water detection, radar systems can offer the unique ɔability of not only detecting the presence of water and resolving its ɔth, but also the potential to distinguishing brackish (or saline) water and ɜsh water.

The procedures presented in this paper can be applied tc swept-ɜquency radar data to isolate the effect of each layer interface on the tal radar signal. Once isolated, the layer interface signals can be used to termine layer thicknesses and the electrical properties of each layer. The lative dielectric constant can be used to estimate the soil moisture content d (when large) the presence of water-bearing layers. The loss tangent of terials is affected, in part, by the presence of conductors. Because salts solution are good conductors, a large loss tangent in a water layer would ggest the presence of brackish or saline water, and a low loss tangent would interpreted as fresh water.

The accuracy of these calculations for ground-water detection with radar still unknown. However, feasibility has been demonstrated. The examples ed for this paper were extracted from other investigations for which the pth of penetration in terrain and pavement materials was limited to centi-tre values. By decreasing the initial low frequency starting point for the ıdar measurements, a dramatic increase in the depth of ground-water detection ıuld be expected.

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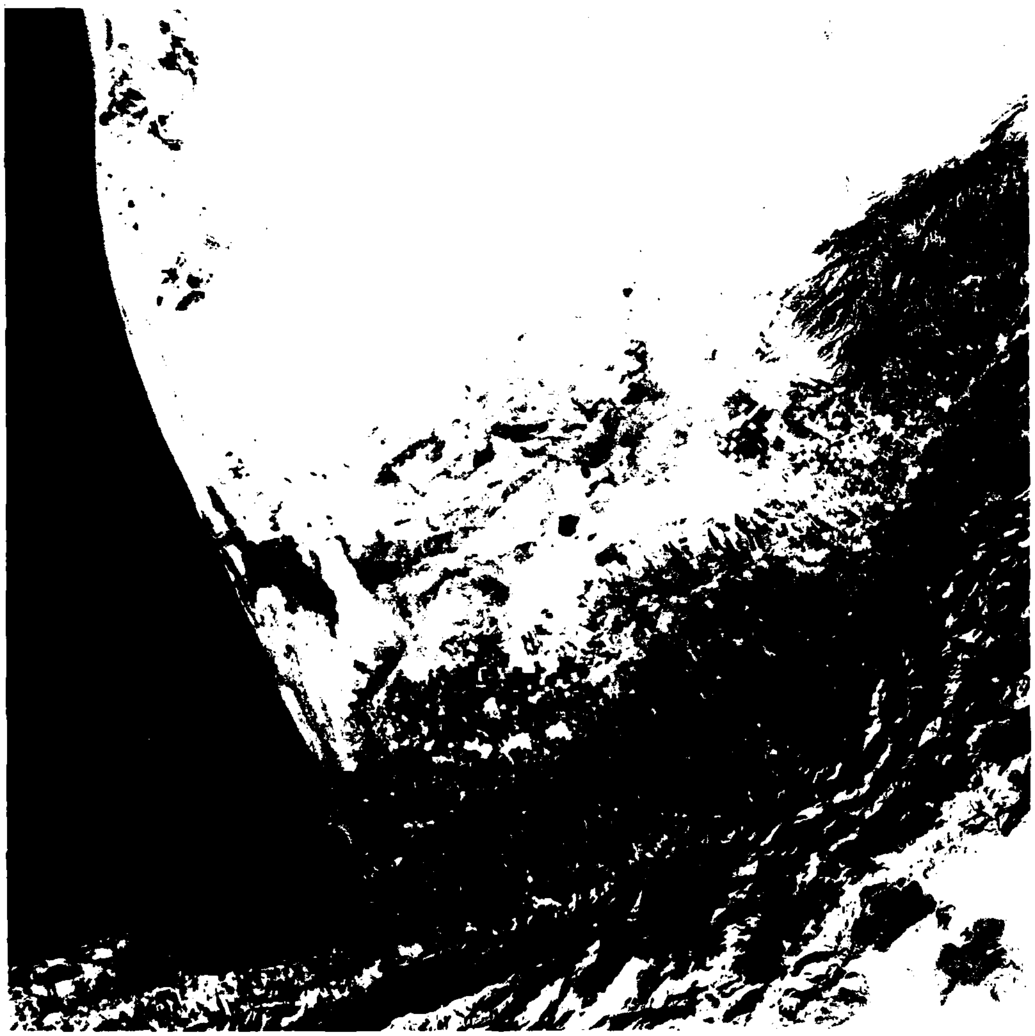

Figure 2. Band 7 Landsat image of the same area shown in Figure 1 (20 November 1976)

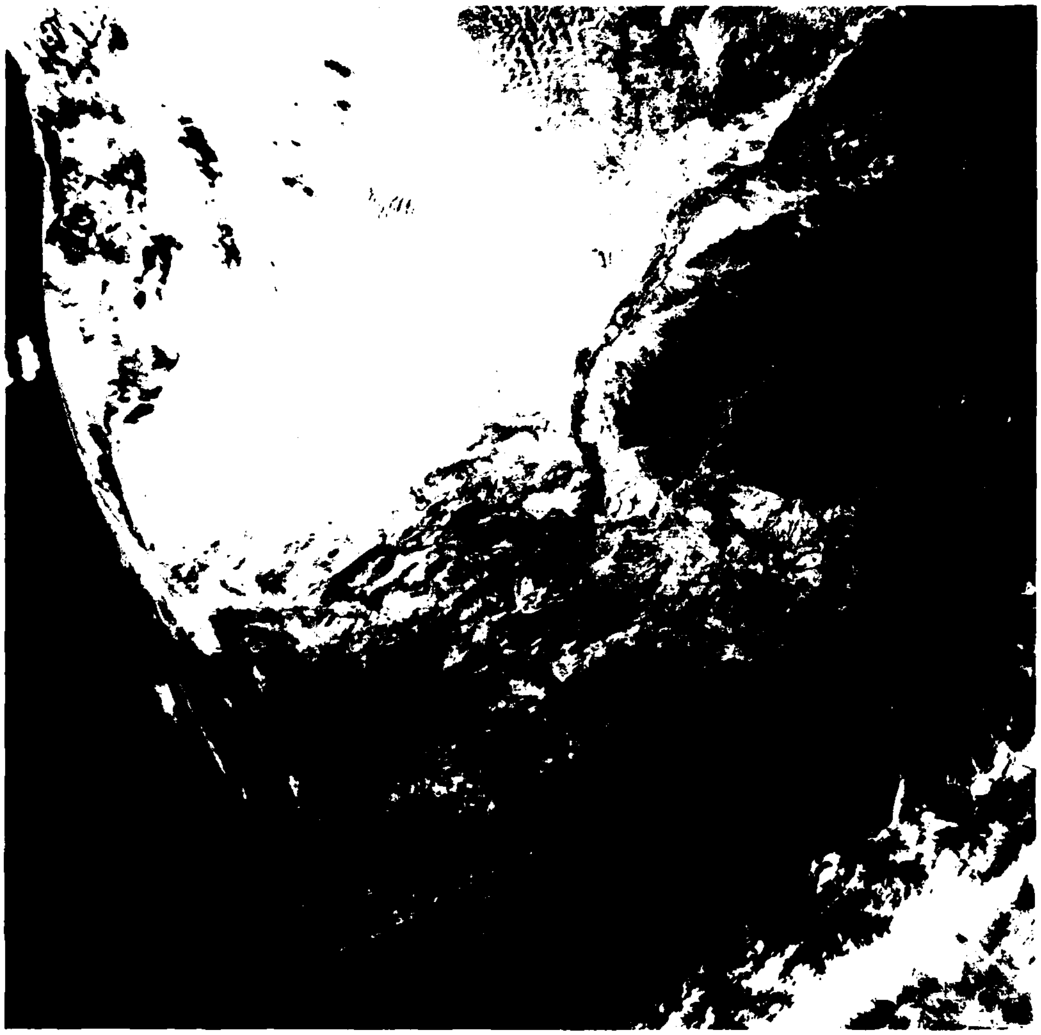

**Figure 1. False color composite Landsat image (shown in black and white) encompassing parts of the Caspian Sea, Iran, and the Soviet Union (1 March 1975)**

# GROUND-WATER DETECTION USING LANDSAT IMAGERY

by

Gerald K. Moore*

Landsat images are commonly used for ground-water exploration. This is n operational procedure that involves the concept of terrain analysis. The rocedures were developed during the 1930's, the 1940's, and the early part of he 1950's when a lot of companies were using aerial photographs for petroleum xploration. Remote sensing capabilities now include different films, ifferent altitudes, a synoptic view (a large areal view of the terrain), and epetitive coverage of an area.

Figure 1 is a false color composite Landsat image, which is very similar o a color-infrared photograph, showing parts of the Caspian Sea, Iran, and he Soviet Union. This paper describes some interpretations that were made rom the satellite images of this area.

In an arid region, ideally the interpretation process should begin with false color composite image obtained at the end of the wet season, which in his part of the world is at the end of the winter months. This particular cene is from 1 March 1975. The Elburz Mountains are in the lower right corer, and some mountain snowpack is apparent. Snow hinders the interpretation, nd the terrain below the snow line is dark and somewhat difficult to see.

A Band 7 image from 20 November 1976 when the sun elevation angle was nly 26 deg above the horizon (Figure 2). Band 7 represents reflected nearnfrared light (0.8-1.1 $\mu$). With low sun elevation angle, there is shadowing f the topography, and these shadows enhance landforms, some drainage lines, nd some fracture systems.

A systematic approach is needed to get all possible information from a atellite image. First, a location map (Figure 3) can be prepared as an overay to Figure 1 to show some of the major landmarks for purposes of registraion. The locations of the two geologic sections (A-A' and B-B') are shown on his overlay.

The drainage network can be delineated from the satellite imagery, and rainage patterns and textures can then be interpreted. Figure 4, prepared as

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* US Geological Survey, EROS Data Center, Sioux Falls, S. Dak.

same profile on several different channels simultaneously, delaying each channel differently, and then stacking all channels.

Migration refers to the process of converting echo times (or reflector position) to depth values and, therefore, to geologic structure. This process requires knowledge of the dielectric properties of the materials present, and could thus not be done expediently for anything more than a two-layer system. Because water tables are linear features, this process would not be absolutely necessary. In most cases, dielectric properties can generally be estimated to determine reflector depth.

Deconvolution refers to the process of finding a suitable filter to either eliminate reverberation within a known layer or to transform an undesirably long and oscillatory pulse wave form into a more ideal impulse-like shape to improve resolution. Any particular antenna can produce a variety of pulse shapes, depending on the terrain and material type encountered; therefore, finding a correct filter for all situations is difficult. However, deconvolution schemes based on only the received data are used extensively in the seismic industry and should be adapted to radar use.

made by separating the antennas produced the model shown in Figure 8.

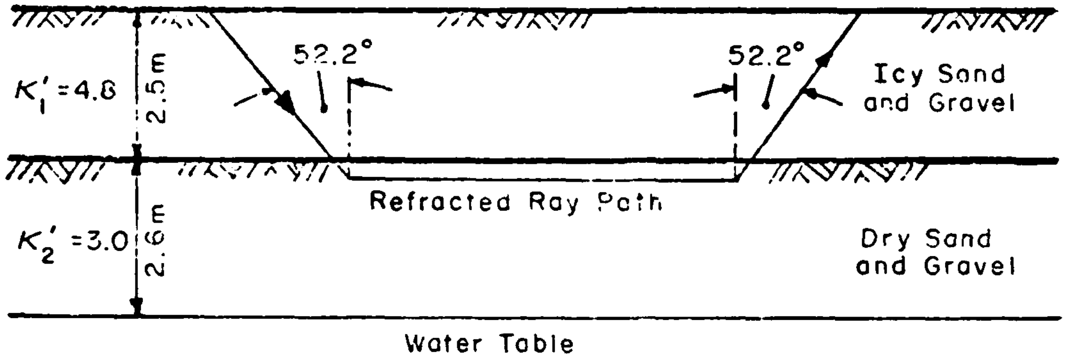
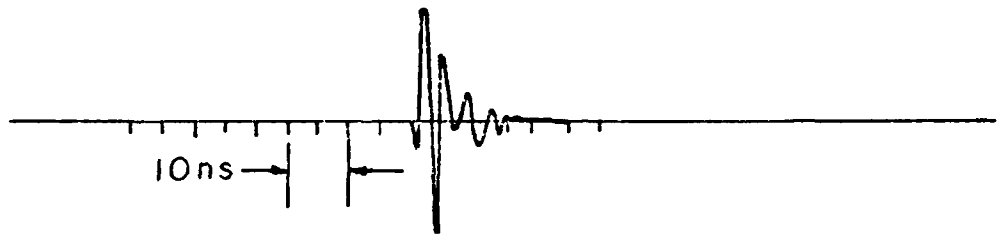


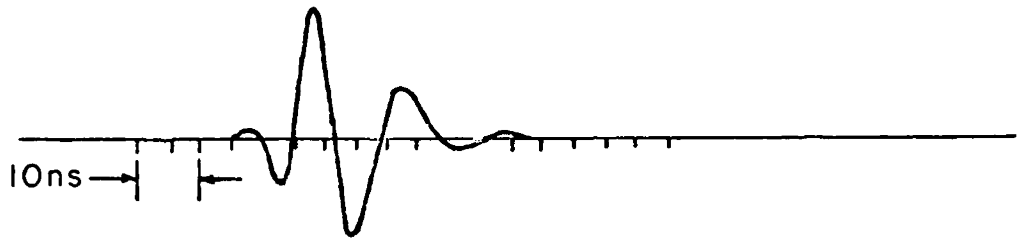

Figure 8. Dielectric model of alluvium on Fort Wainwright. The refracted ray was observed on a Warr sounding

Figures 3 and 4 are profiles over a glacial outwash of sand and gravel located at Fort Greely, Alaska. The dielectric constant of the material was measured both from the slopes of diffraction hyperbolas (generally between 3 and 9) and from soundings (5.5). Well logs had indicated the existence of a perched water table at a depth of 9 to 14 m. In both figures, this water table can be seen as the last faint reflection about halfway down the record. That this is the water table is deduced from the fact that it is not parallel with the surface (which tilts from north to south) and is also at about the right depth considering a dielectric constant of approximately 5.5. The numerous diffractions originating in the top half of the record are the hyperbolas mentioned above and are primarily responses to silt-filled wedge-like structures, which could be fossil ice wedge casts.

Future improvements in radar must come in the area of digital signal enhancement, as the physical system is about at its practical limit with respect to pulse shape, noise reduction, and antenna-ground coupling (for dry ground). Three techniques in need of attention are stacking, migration, and deconvolution. One company (Xadar Corporation of Springfield, Virginia) now makes a radar with a stacking capability in a digital, single trace mode. In a static antenna position, the signal stacking vastly reduces incoherent noise. If this capability could be incorporated into a profiling mode so that stacking would be continuous while the antennas moved, then coherent noise (as from undesirable point reflectors) could be eliminated, while responses from linear reflectors such as a water table could be enhanced by recording the




a. Pulse in air




b. Pulse in ground, k' ≈ 10

Figure 6. Free space and ground pulse wave forms for GSSI Model 3105 antennas

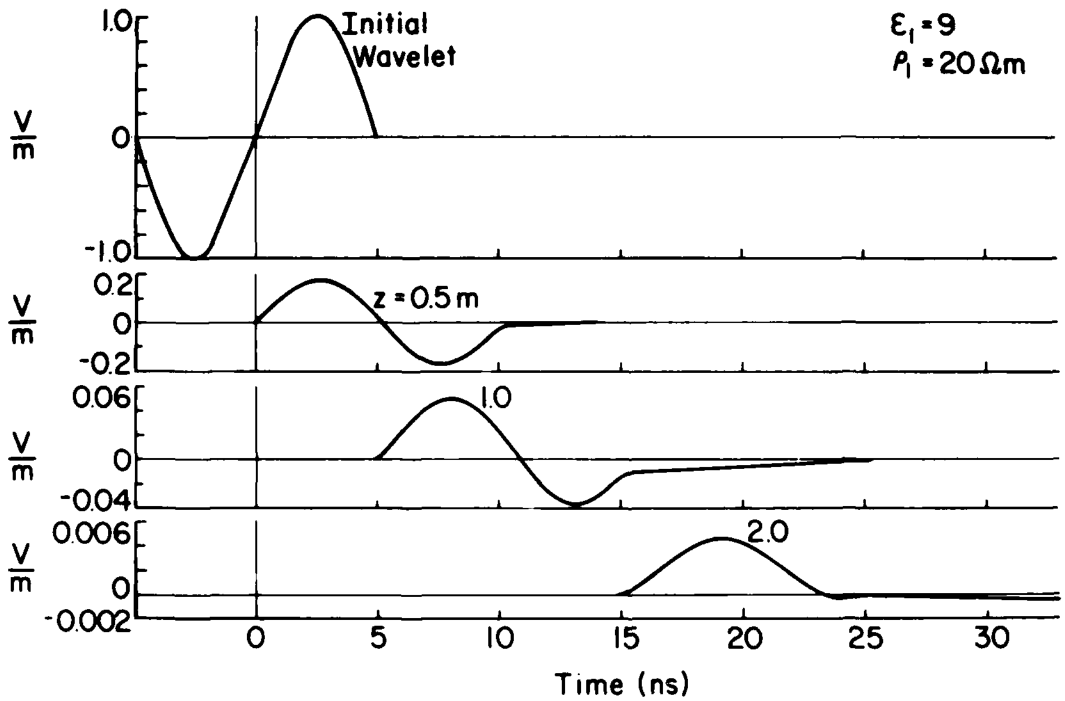



Figure 7. Distortion of a 10-ns wavelet propagating a distance Z in a conductive media

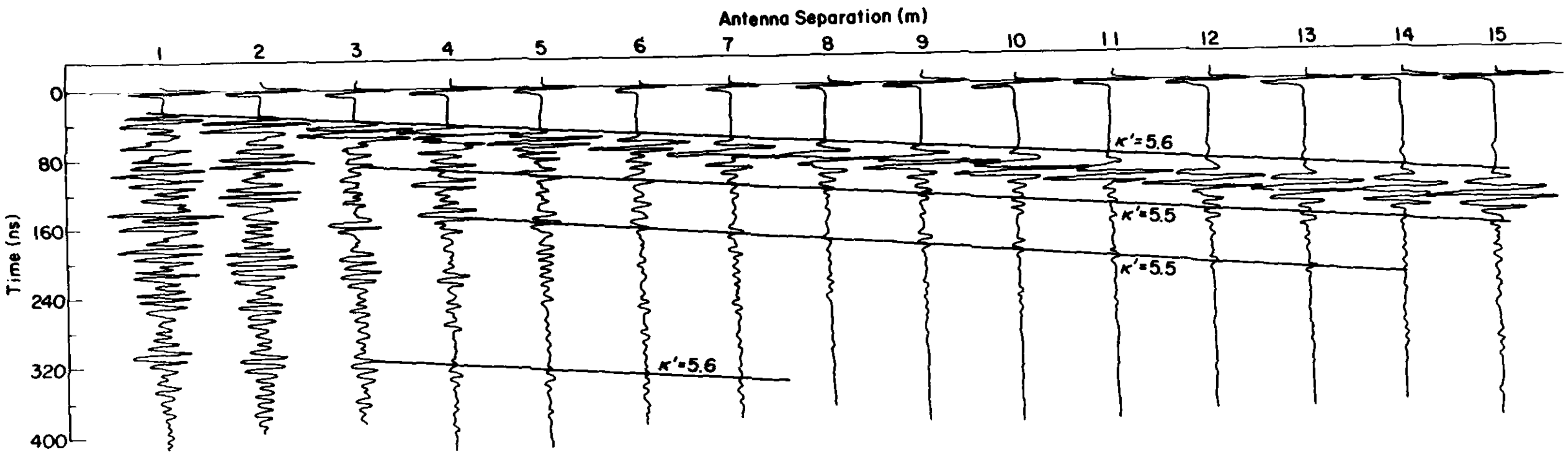



Figure 5. Wide-angle refraction and reflection sounding over glacial outwash with the CSSI Model 76 antennas. Note the difference in pulse shape between Figure 6b and in this figure at 15 m. The first arrival shown here is a surface ground wave

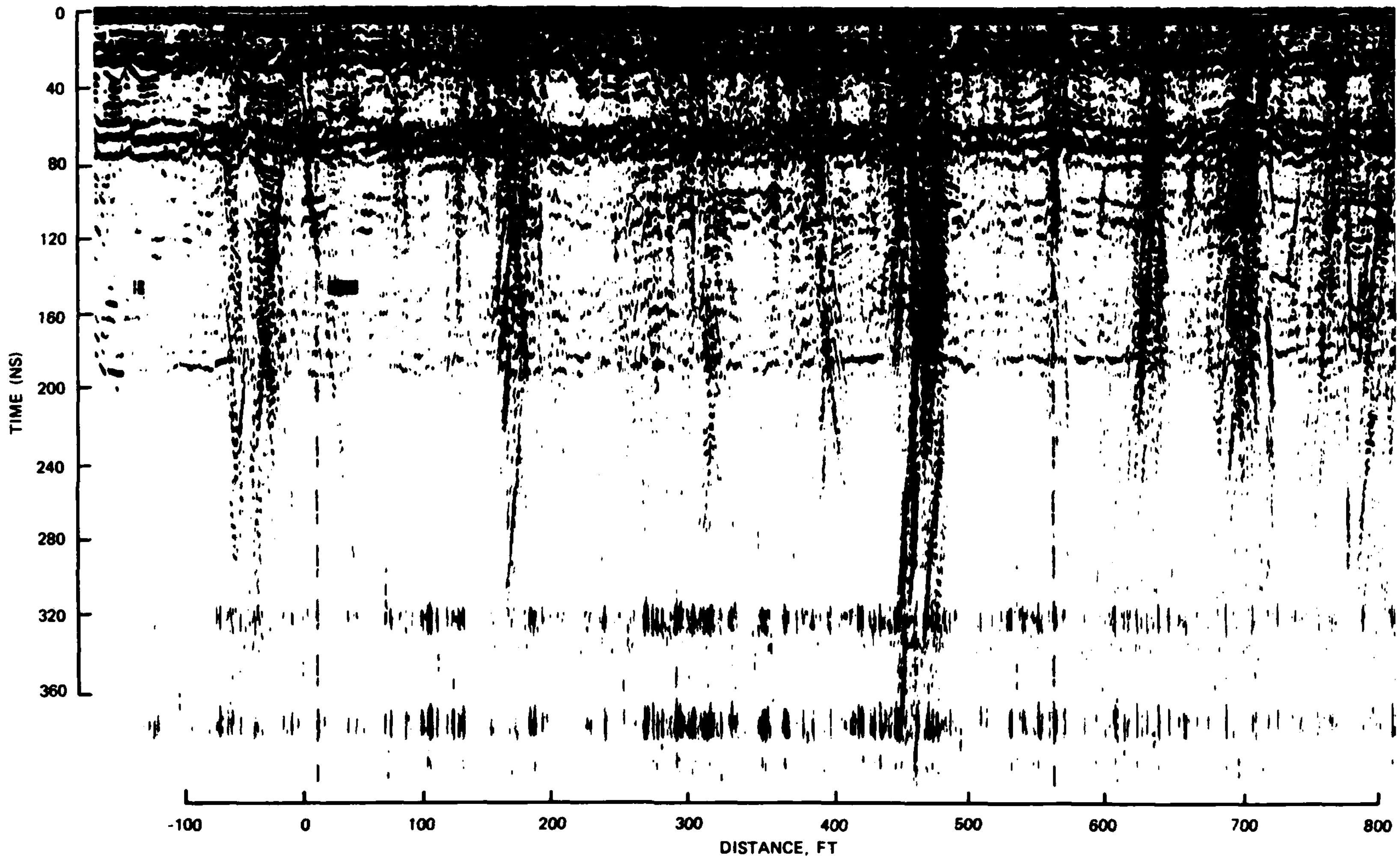



Figure 4. Radar profile over glacial outwash at Fort Greely, Alaska taken 30 m east of Figure 3. The faint reflection at 170-190 ns is the water table

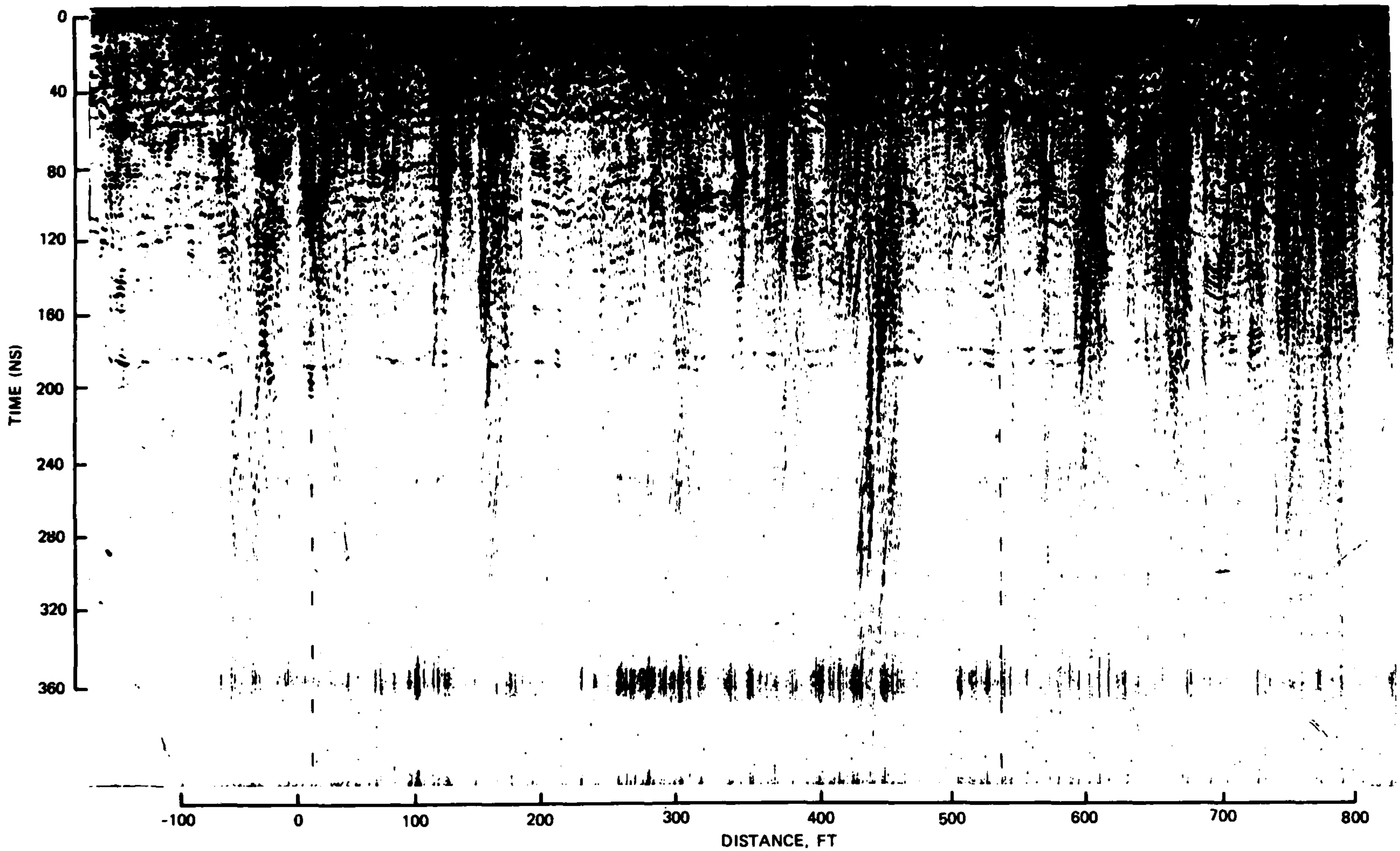



Figure 3. Radar profile over glacial outwash at Fort Greely, Alaska. The faint reflection at 170-190 ns is the water table

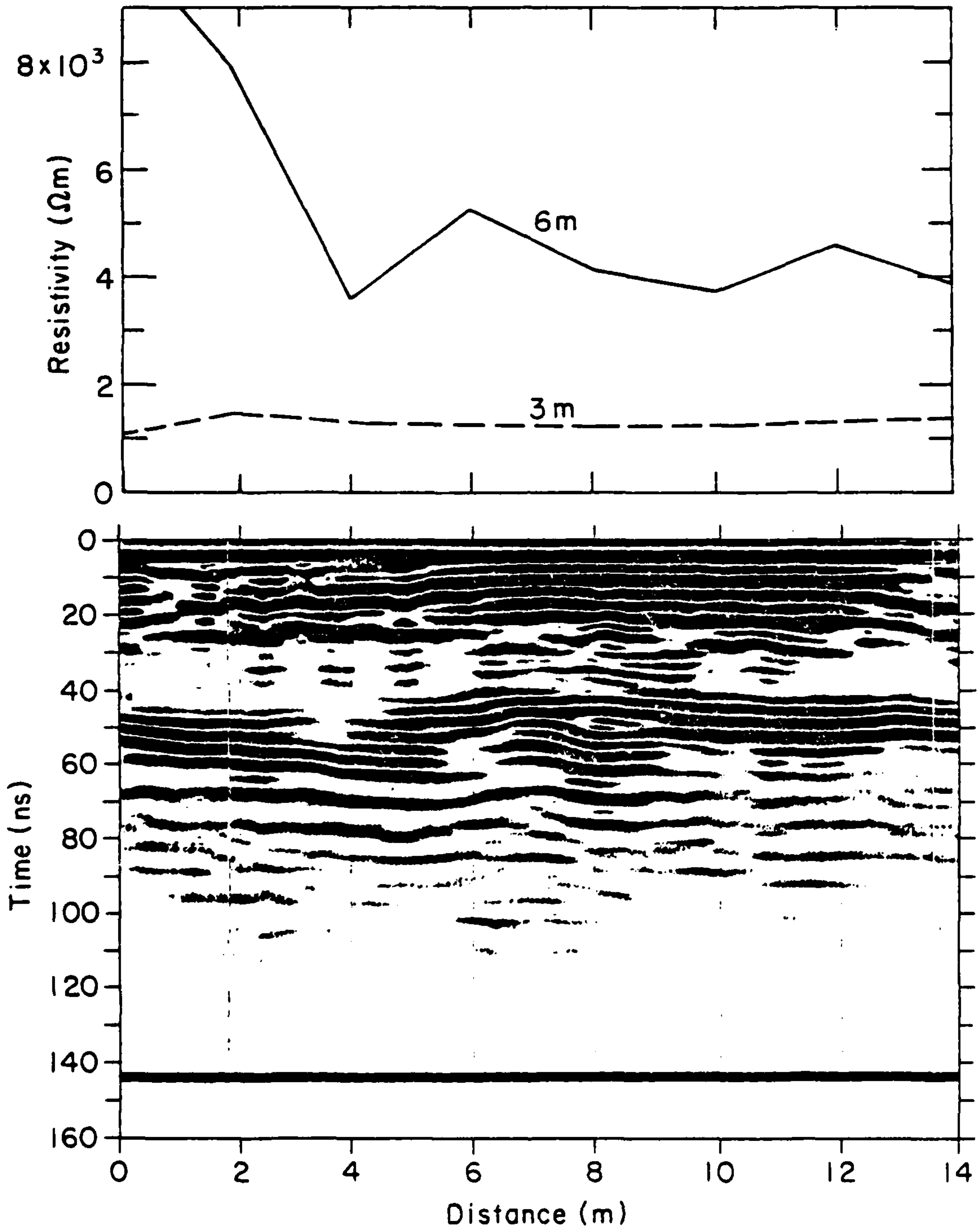



Figure 2. Radar and resistivity profiles at alluvium on Fort Wainwright, Alaska. The resistivity profiles were made using magnetic induction, and the curves are labeled according to depth of penetration

operation would not be feasible. The subsurface data are usually displayed as a consecutive series of linear scans (see Figures 2-4) along which darkness of tone represents signal intensity. Thin white lines defining dark bands are signal zero crossings. The display is the same as that of a marine fathometer. Separate traces of signal wave forms are also possible, as shown later in the reflection and refraction sounding of Figure 5.

A variety of antennas are available from the different companies manufacturing radar equipment, and they radiate from 30 to 1000 MHz in their pulse spectra. Although all antennas are excited by a similar half-cycle pulse, they all ring to some extent and emit a decaying oscillation, such as that shown in Figure 6 for the GSSI Model 3105 antennas, or as seen in the 15-m trace of Figure 5 for the GSSI Model 76 antennas. Theoretically, the best "ideal" pulse that could be radiated would be a doublet rather than a single spike because of the physical restraint of no radiation of DC energy.

Limitations to depth of exploration come from a variety of mechanisms, with the most serious being highly reflective interfaces, poor antenna coupling to ground, diffuse scattering, ringing from highly reflective surface layers, and signal attenuation due to either dipolar or ionic conductivity mechanisms. The latter two factors are generally due to the presence of water and because subsurface radar usually works best around 100-300 MHz where the total loss due to water is usually minimized. Figure 7 shows the attenuation suffered by a doublet (spectral peak ~ 100 MHz) when propagating over a round trip of 2 m in conductive material. The attenuation of 56 db in 20 Ωm material is fairly near the performance figure (≈70 db) of some radar systems.

Figures 2, 3, and 4 are examples of ground-water detection profiles at two sites in Alaska. Figure 2 gives a radar and resistivity profile over an alluvial sand and gravel on Fort Wainwright in Fairbanks, Alaska. The profiles were made within 100 m of the Chena River, which had an elevation that was 5.1 m lower than the ground surface of the geophysical profiles; therefore, we assume that the water table was 5.1 m below the ground surface. The radar profile shows two distinct reflectors. The topmost, at about 35 ns, is thought to be the bottom of the seasonally frozen active layer.* The second more diffuse reflection, at about 65 ns, is the water table. These profiles, the observed river elevation, and additional data from wide-angle soundings

* The profiles were made in April 1981; there is no permafrost at this site.

RADAR DETECTION OF GROUND WATER

by

Dr. Steven A. Arcone*

During the past 10 years, commercial and private organizations have developed ground-penetrating radar (GPR) systems for geophysical ground exploration. These systems amalgamate the principles of conventional surface radar and seismic exploration techniques. They have been used for profiling the depths of glaciers, lake ice, brine intrusions, peat bogs, active layers, ground-water tables, and lake bottoms. As with seismic techniques, the responses of the radar signal to targets whose dimensions are comparable to or smaller than the transmitted wavelength can result in complicated diffraction patterns.

A schematic drawing of the operation of subsurface radar is given in Figure 1. A broadband, resistively loaded, bowtie-type dipole antenna (or sometimes a TV yagi array) radiates a short pulse whose frequency spectrum is usually in the VHF-UHF range. The pulse generally lasts about 5-15 ns and has a pulse repetition frequency (PRF) of about 50 kHz. A separate antenna is used for reception because some echoes return so soon that single-antenna

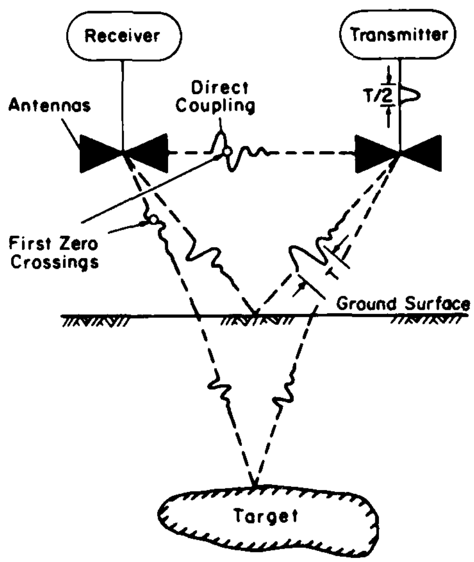



Figure 1. Operation of subsurface radar

* US Army Cold Regions Research and Engineering Laboratory, Hanover, N. H.

Table 1

Swept-Frequency Radar Measurements

| Layer No. | Material* | Results From Analysis Program: Optical Depth m | Relative Dielectric Constant $\varepsilon_r$ | Dielectric Loss Tangent $\tan \delta_d$ | Layer Thickness m | Computed Water Content g/cm$^3$ | True Values: ℄ Thickness m | Water Content g/cm$^3$ |
|---|---|---|---|---|---|---|---|---|
| | **Example 1: Highway Embankment** | | | | | | | |
| 1 | Asphalt pavement | 0.415 | 3.5 | 0.163 | 0.222 | 0.0 | 0.210 | 0.0 |
| 2 | Clay-gravel base (SM) | 1.000 | 8.555 | 0.014 | 0.200 | 0.18 | 0.209 | 0.14 |
| 3 | Silt foundation (CL) | -- | 12.091 | -- | -- | 0.24 | -- | 0.28 |
| | **Example 2: Sand Soil Site, Position 1** | | | | | | | |
| 1 | Sand (SP) | 0.845 | 6.916 | 0.180 | 0.321 | 0.152 | -- | 0.096 |
| 2 | Sand subgrade (SP) | -- | 26.720 | -- | | 0.434 | -- | -- |
| | **Example 2: Sand Soil Site, Position 2** | | | | | | | |
| 1 | Sand (SP) | 1.047 | 6.172 | 0.130 | 0.421 | 0.137 | -- | 0.096 |
| 2 | Sand (SP) | 1.776 | 17.553 | 0.070 | 0.174 | 0.314 | ** | -- |
| 3 | Buried metal plate | -- | ** | -- | -- | -- | -- | -- |

* The appropriate Unified Soil Classification System symbol is given for each soil layer.

** The equations for relative dielectric constant cannot be applied for the metal plate target; however, the computed power reflectance for the analysis procedure for the underlying sand (SP) layer (0.60 m deep) was 1.07 and, by definition, the reflectance from a metal plate is 1.0.

Lundien, J. R. 1972a. "Determining Presence, Thickness, and Electrical Properties of Stratified Media Using Swept-Frequency Radar," Technical Report M-72-4, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Lundien, J. R. 1972b. "Noncontact Measurements of Foundations and Pavements with Swept-Frequency Radar," Highway Research Record, No. 378, pp 40-47.

Lundien, J. R. 1978. "Feasibility Study for Railroad Embankment Evaluation with Radar Measurements," Miscellaneous Paper S-78-10, US Army Engineer Waterways Experiment Station, Vicksburg, Miss. (Also published under the same title as: Report No. FRA/ORD-79/08, February 1979, US Department of Transportation, Federal Railroad Administration, Office of Research and Development, Washington, DC.)

Lundien, J. R. 1981. "Radar Evaluation of Railroad Embankments," Memorandum for Record, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

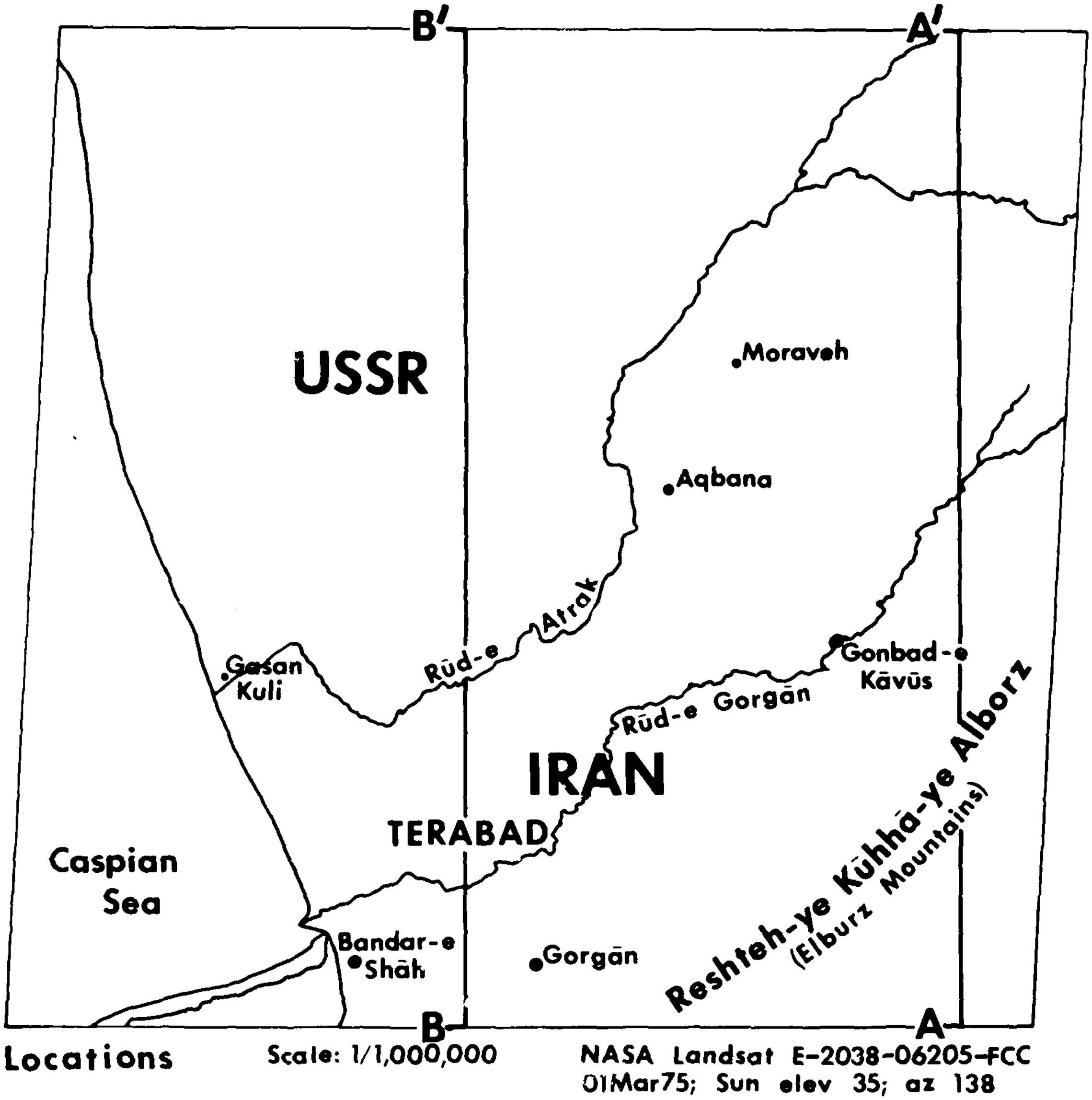



Figure 3. Location overlay for Figure 1 showing major landmarks and geologic sections A-A' and B-B'

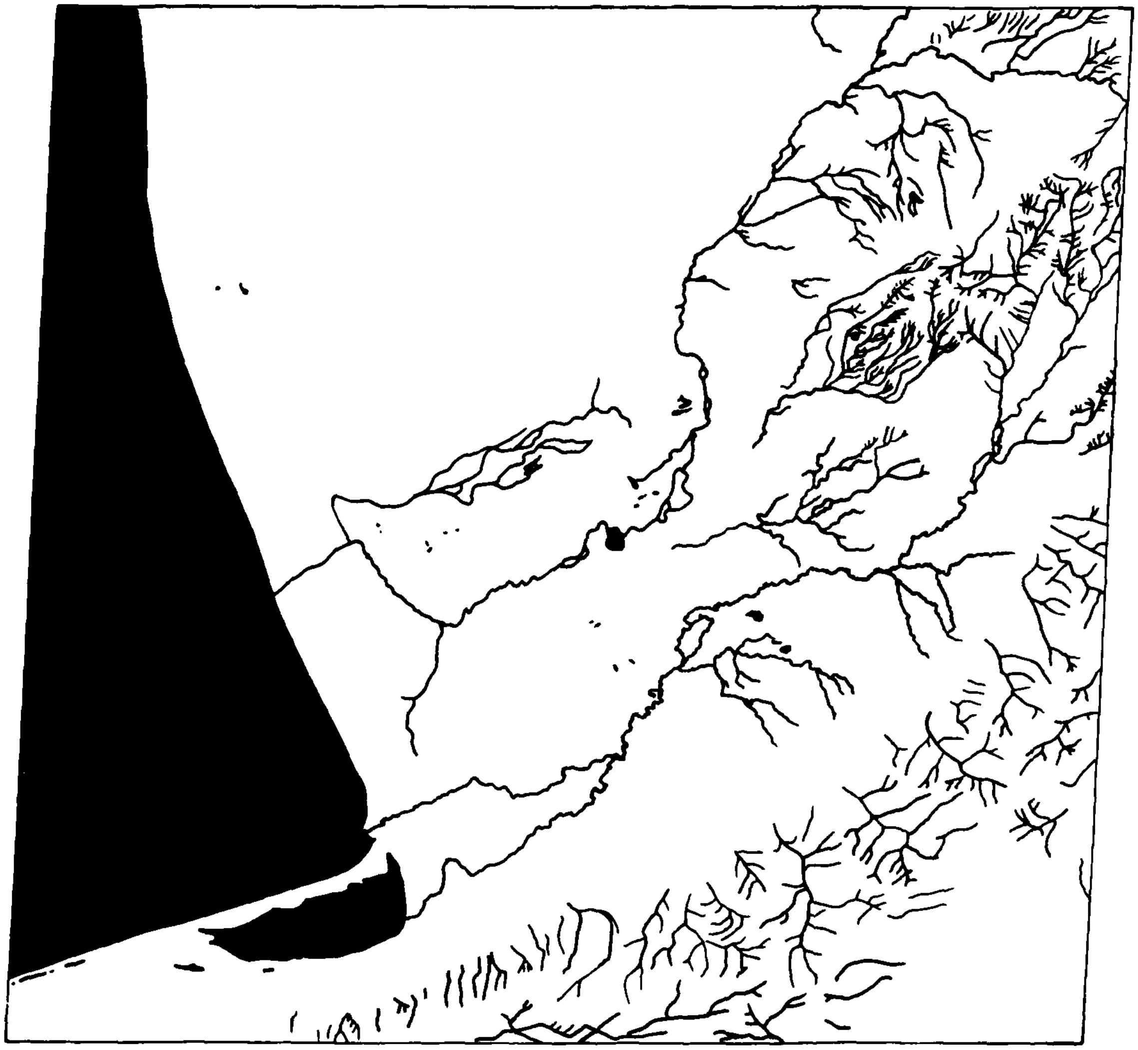


Figure 4. Drainage overlay prepared for Figure 2

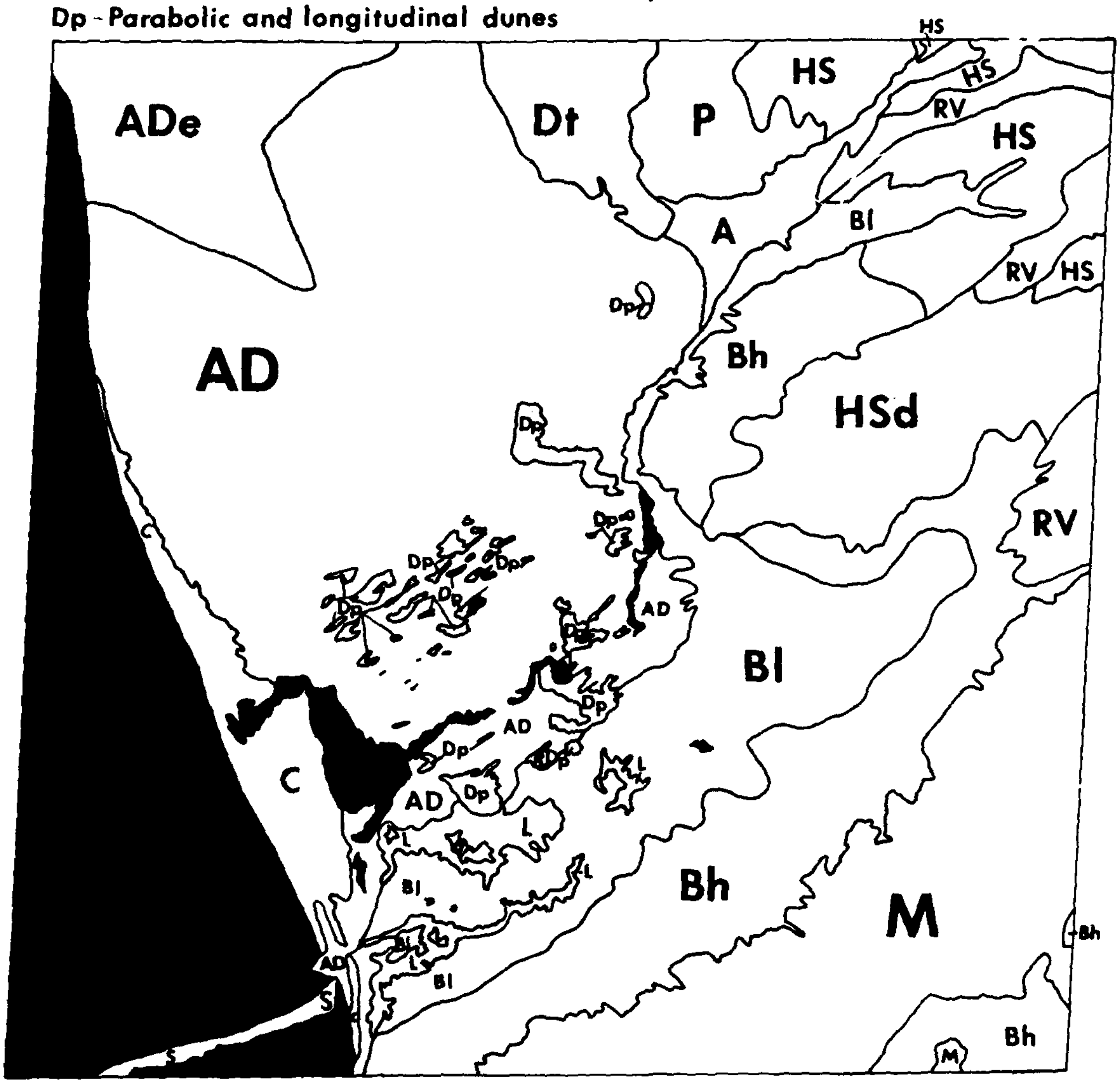
an overlay to Figure 2, shows some interesting features. The Rūd-e Atrak (Atrak River) (refer also to Figure 3) flows southwestward but then turns to the northwest before reaching the Caspian Sea. Several centripetal drainage patterns can also be seen. There are likely structural causes for these flow and drainage patterns. Many streams originate in the Elburz Mountains; however, at the foot of the mountains, they flow beneath the surface. This change in flow pattern could be indicative of the geology (Figure 4); other drainage patterns shown on Figure 4 could be indicative of fracture patterns.

Figure 5 (prepared as an overlay to Figure 1) is a landforms map. This

3-green

EXPLANATION

A - Stream valley alluvium
AD - Arc delta
ADe - Slightly eroded delta
Bh - High bajada; steep slope
Bl - Low bajada; shallow slope
C - Chenier; beach ridges
Dt - Transverse dunes
Dp - Parabolic and longitudinal dunes
HS - Hill slope
HSd - Dissected hill slope
L - Natural levee
M - Mountains; mature topography
P - Pediment
RV - Ridge and valley topography
S - Spit




Landforms Scale: 1/1,000,000 NASA Landsat E-2038-06205-FCC 01Mar75; Sun elev 35; az 138

Figure 5. Landforms overlay prepared for Figure 1

map shows the Elburz Mountains and a ridge and valley topography. The parallel ridges and valleys probably represent folded sedimentary rocks. There is a series of alluvial fans that merge along the foot of the mountains to form a bajada. In addition, some hill slopes (HS and HSd areas) are also visible. A very large delta (indicated by AD and ADe) occupies all of the central part of the image. Superimposed on some of the other landforms are a series of sand dunes (Dt and Dp). There are transverse, parabolic, and longitudinal dunes. The little area called a pediment (P) appears to be an extension of the bedrock that is forming the hills.

The vegetation map, Figure 6 (prepared as an overlay to Figure 1), shows areas of dense natural vegetation and agricultural areas. Vegetation can indicate places where ground water is close to the surface. Agricultural areas indicate nonsaline soils and perhaps fresh, rather than brackish or saline, ground water.

Mapping the structure is somewhat difficult because the mountainous areas are covered with vegetation. Thus, a map showing strikes and dips (Figure 7) was prepared as an overlay to Figure 2 to aid in the interpretation process. The directions of the dips of the rocks could be determined at 160 locations.

The next step is a complete geologic structure map, Figure 8 (prepared as an overlay to Figure 2) showing the axes of anticlines and synclines based on strikes and dips. Also, in some places, evidence of faulting could be seen. Two of these areas are indicated by triangular facets (tf) on the overlay. Some of the drainage patterns also indicate faults in the rocks. Faults are significant in bedrock areas because they can form conduits for ground water. They can also be ground-water dams. A lot of the linear features have to be called lineaments (dashed lines). These features may or may not be fractures in the rock. As part of a geologic or hydrologic interpretation, the lineaments can be assumed to be fractures of some sort.

The next step is to draw a geologic map based on these overlays. An alternative step is the construction of cross sections, Figure 9 (refer to Figure 3). A series of cross sections helps to get a three- dimensional picture of the geology in the area. The Elburz Mountains consist of massively bedded and block-faulted sedimentary rocks. In part of the area, these rocks form a ridge and valley topography; in other parts of the image, they are overlain with either dunes or alluvial sediments or both.

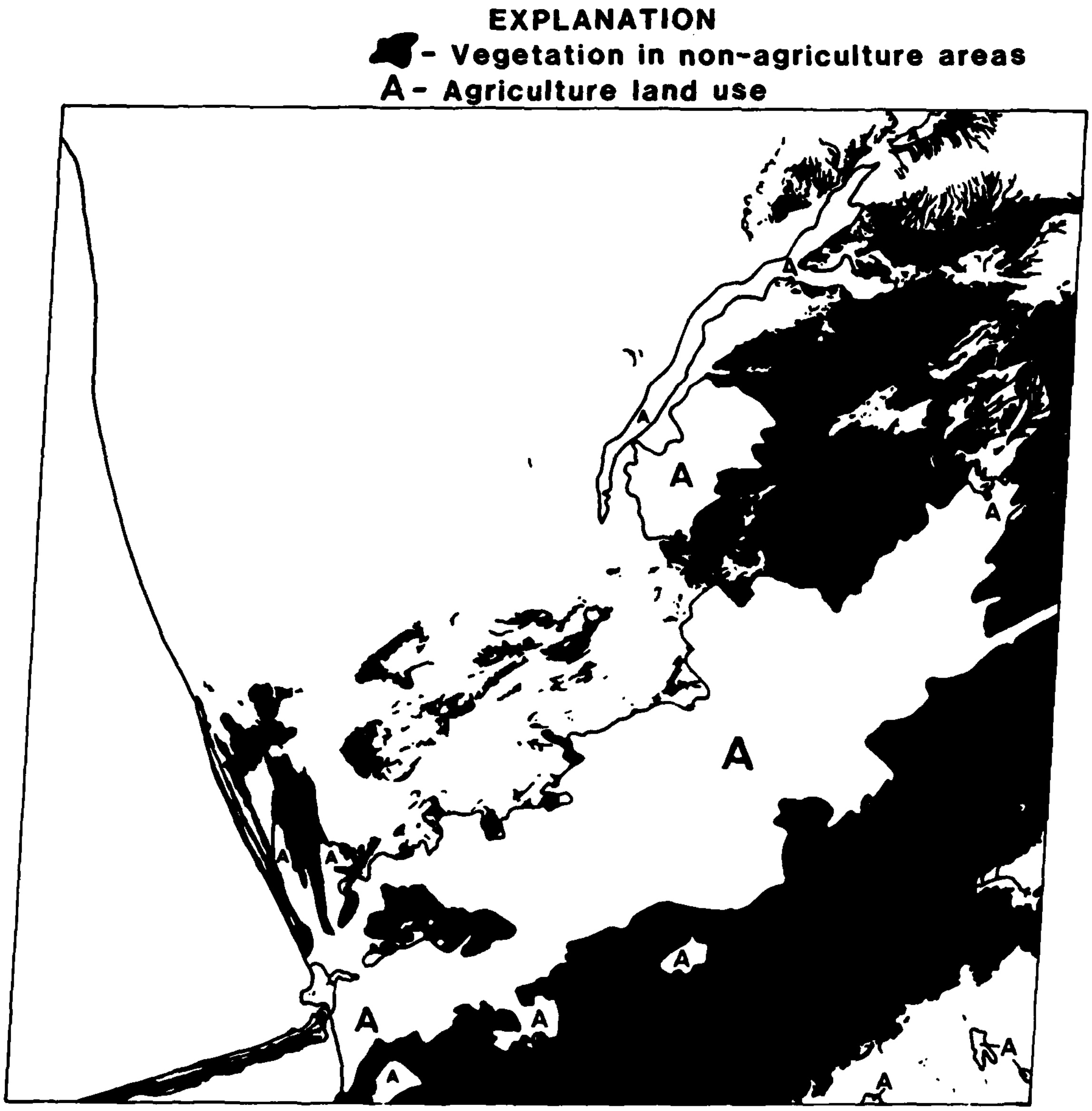



Figure 6. Vegetation overlay prepared for Figure 1

Optional - black

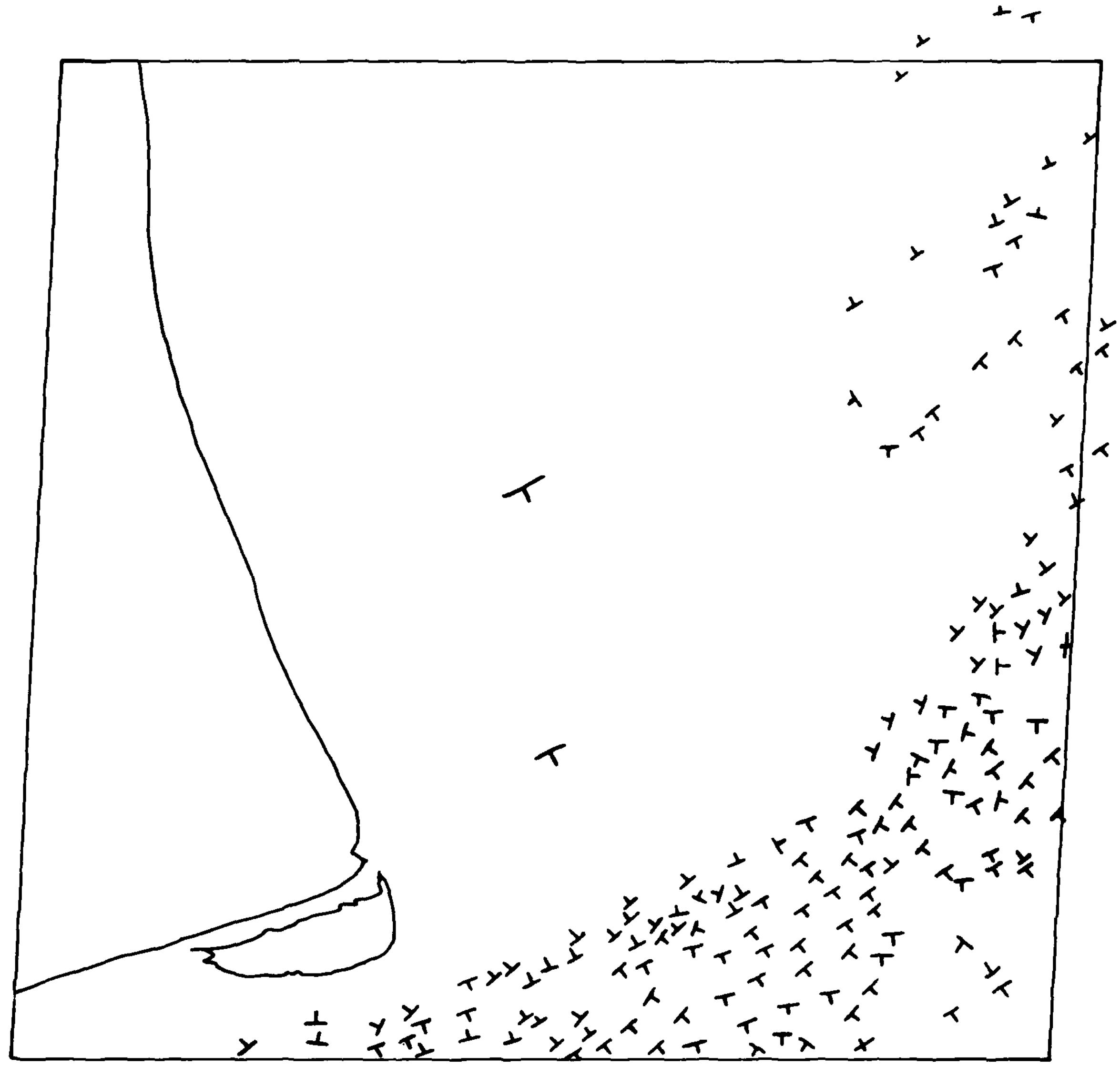




Figure 7. Overlay prepared for Figure 2 to show strikes and dips

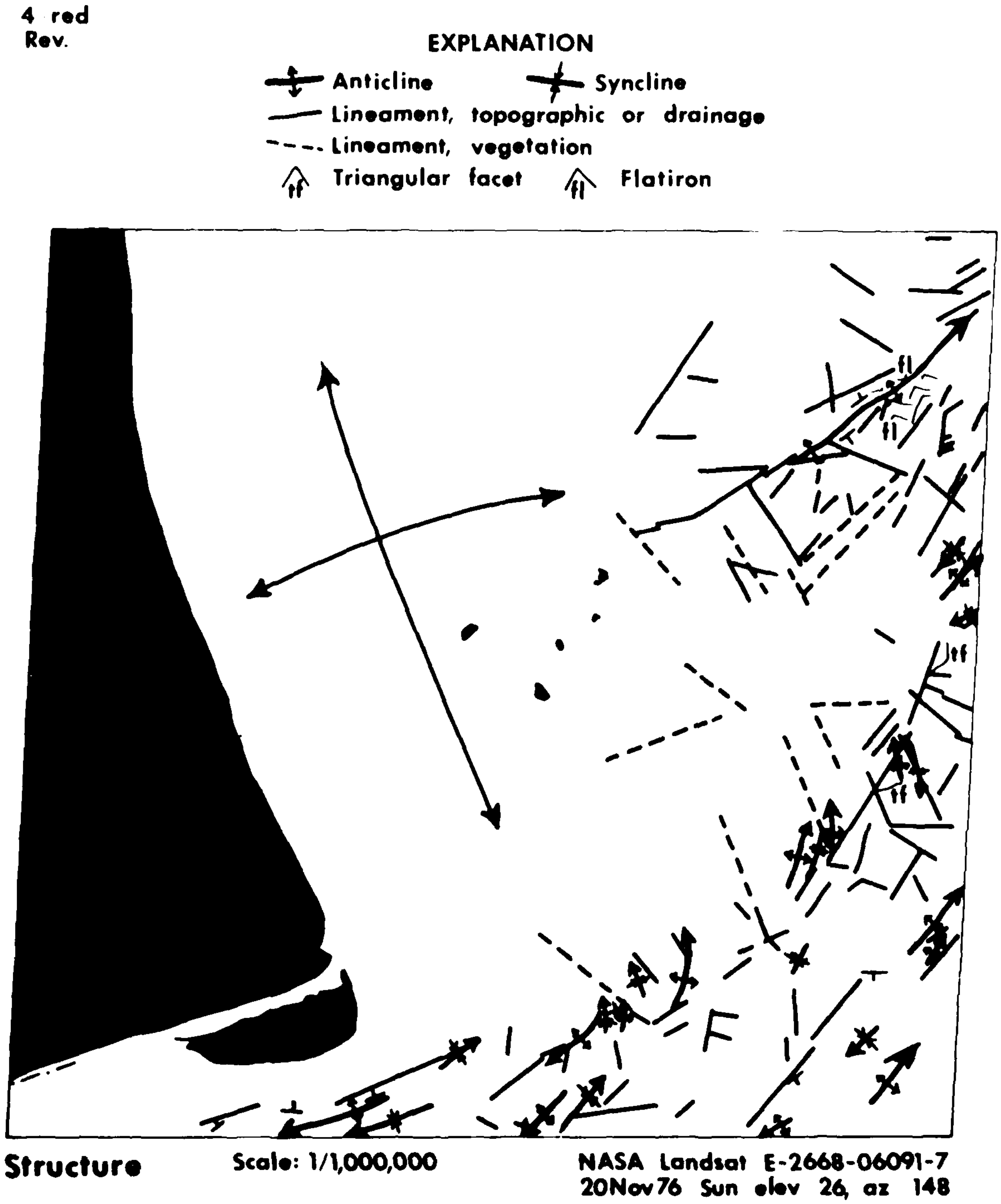



Figure 8. Geologic structure overlay prepared for Figure 2

**5-black**
**Rev.**

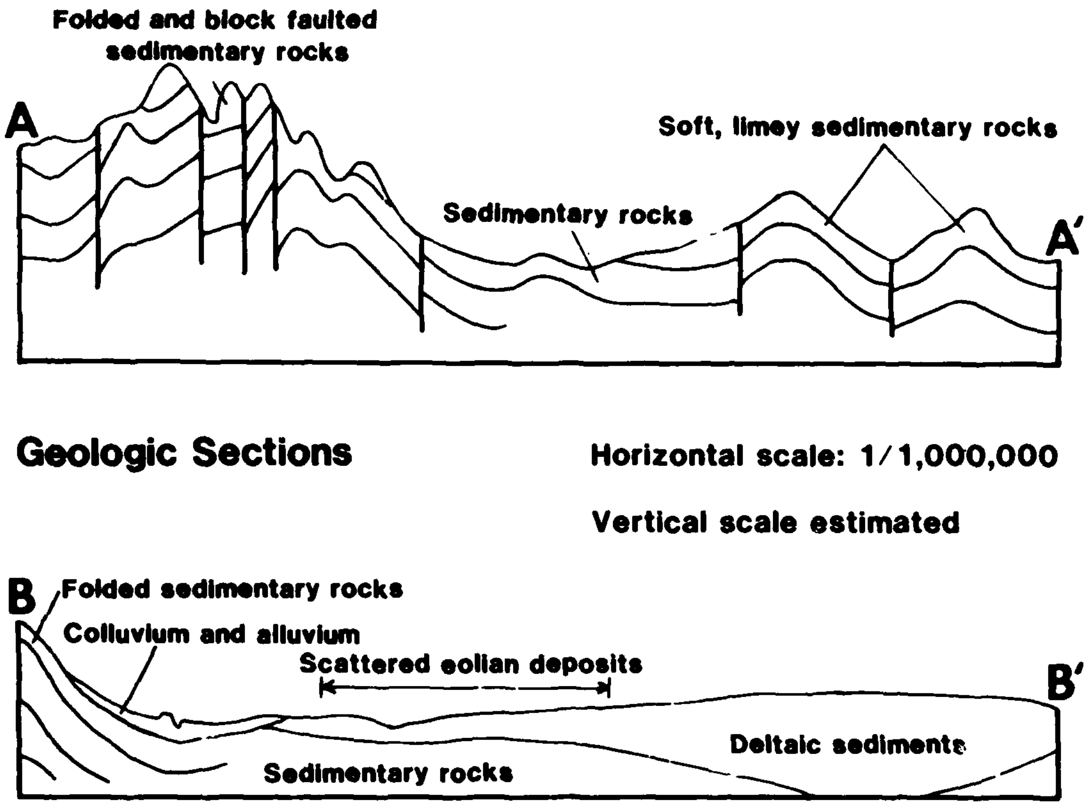



Figure 9. Geologic cross sections A-A' and B-B' (refer to Figure 3)

The final interpretive overlay is an aquifer map, Figure 10 (prepared as an overlay to Figure 1). In the bedrock mountain areas, the only places for ground-water occurrence is the fractures. At lower elevations, material that has eroded from the mountains forms alluvial fans and bajadas. These materials are thin near the mountains, but farther down into the valley they could be fairly thick and provide a suitable aquifer. In all of the low-lying areas, a high water table would normally be expected. The water table is probably just a few feet to a few metres below land surface in the delta area, but there is no vegetation growing there. The reason for the lack of vegetation is probably attributable to salt water underlying the land surface at a very shallow depth. In part of the area, there could be a very thin layer of fresh water overlying the salt water. Thus, patches of vegetation occur on the higher elevations, but not any lower.

These overlays show the results of an interpretation of the images. A prediction of well yields also can be made on the basis of previous experience. If an interpreter has no knowledge of the specific area, then his predictions have to be based on experience gained elsewhere. A well drilled close to the edge of the bedrock would be expected to have a fairly low yield (perhaps only a few gallons a minute). At lower elevations, there may be yields of 50, 100, or 300 gpm per well. Farther out in the lowlands, wells will produce just a few gallons a minute before pumping salt water.

About 2 weeks were required to interpret this scene of 13,000 square miles, including making all of the overlays and writing a report, so it is not a labor-intensive job. Our cost right now is running about $70,000 per man per year. Therefore, this job, which represents 2 weeks of direct hour labor, costs about $3000.

The importance of selecting a scene to get the maximum information possible has been discussed. Two other considerations are the need for image enhancement and analysis. The images used as examples not enhanced. They were Landsat standard products, as obtained from the EROS Data Center. Enhancement almost never shows anything that does not appear on the raw images; however, there are a few exceptions. The purpose of enhancement is to make image interpretation faster and easier and to ensure that you do not miss anything. Analysis is the process of classifying land use and land cover. A particular land cover is sometimes a key to the presence or salinity

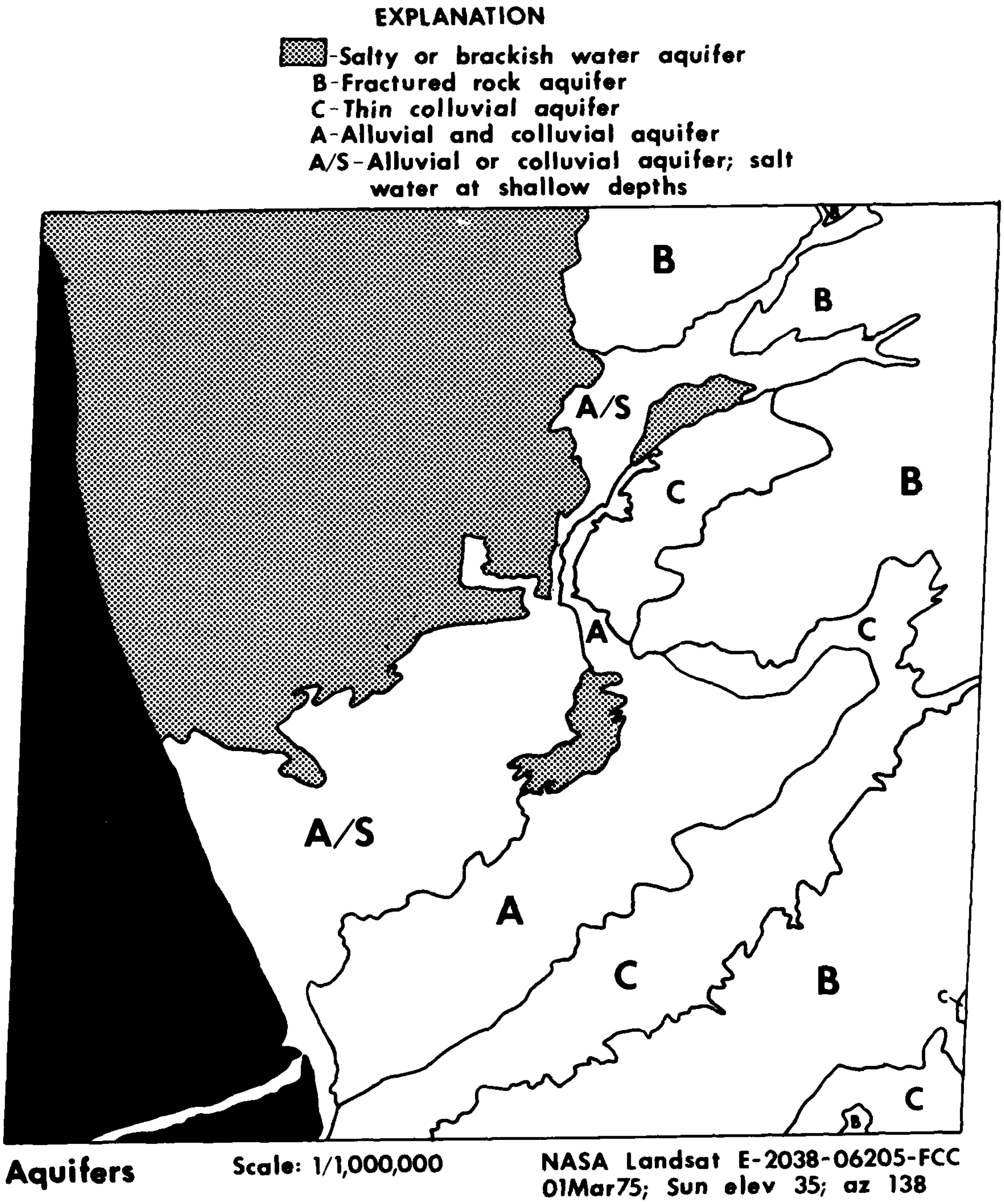



Figure 10. Aquifer overlay prepared for Figure 1

of ground water. However, the classification of land cover has not proved to be particularly useful for ground-water exploration.

After interpreting landforms, drainage, cover types, and lineaments, geologic and hydrologic interpretations can be made. A geologic interpretation consists of mapping the surface geology and then projecting this into the subsurface. Once the processes that produced landforms and the subsurface geology are interpreted, the tectonic processes that were involved can be determined. The end product is a three-dimensional geologic model. A hydrologic interpretation to infer the permeability and porosity characteristics of materials, the aquifer boundaries, the depth of the water table, and ground-water salinity is then possible.

All of the information that the military is going to need for selecting well locations cannot be obtained from Landsat images. However, Landsat is a reconnaissance tool and a means of rapidly covering a large area; it can be used to select the most promising areas for electrical resistivity, seismic refraction, or ground-penetrating radar surveys. Potential users should not assume that Landsat is the only tool that can be used or even that it is the ideal tool to be used. Naturally, a 30-m resolution, instead of the 80-m resolution that we get from Landsat, would be preferable. With only an 80-m resolution, reliable interpretations cannot be made for some areas. Whenever possible, areas located on Landsat imagery should be checked with stereoscopic aerial photographs. Undoubtedly, for many areas of the world, some kind of ground-based geophysical technique will be necessary because remote sensing just looks at the land surface.

# USING VEGETATION AS INDICATORS OF NEAR-SURFACE GROUND WATER IN AN ARID ENVIRONMENT

by

Melvin B. Satterwhite*

## Introduction

The survival of man in an arid environment has been contingent on quiring water of acceptable quality and quantity to satisfy his needs. cause man can be quite mobile, he can either move from one area to another search of water or he can transport water from areas having ample water to eas having little or no water. Unlike man, seeds and other plant propagules e at the mercy of various natural transportation mechanisms (e.g., wind or nning water) for reaching sites having adequate water for establishment and rvival. Seeds can lie dormant in dry soil for many years; however, when the il becomes sufficiently moist, they can germinate. Certain plant species come dormant during periods of drought. Other plants survive drought by eir protected growing tissue on the stem or root. Plants, as functioning ological entities, must obtain enough water to satisfy their physiological quirements. Additionally, the quality of the water obtained must not place ress on the plant's tolerance mechanisms.

Vegetative patterns indicative of near-surface ground water are usually sed on how a plant uses water for growth and other physiological processes. understanding of the normal seasonal growth stage and water needs of plants the area of interest, coupled with soil moisture ınd climatic data, can sist in the task of using remote sensors to locate sources of possible ound water. Studies have shown that the occurrence and distribution of ant species and plant communities in arid and semiarid regions are related the soil moisture conditions of various landform units (Satterwhite and len 1980; Yair and Danin 1980). To increase the possibility of establishing rect vegetation-ground water relations, vegetative indicators of ground ter must be used in conjunction with knowledge of the local geologic conditions. For example, vegetation growing on the slopes of massive granitic

US Army Engineer Topographic Laboratories, Fort Belvoir, Va.

outcrops would be less useful as an indicator of near-surface ground water than would an equivalent amount of vegetation growing on the margins of a dry stream channel.

To establish the pattern relations that can be used to predict the occurrence of near-surface ground water by remote sensing techniques, selected plant species and their habitats must be evaluated with reference to the associated terrain features, soil conditions, and morphologic and physiologic characteristics of these species. Even with limited knowledge, remote imagery can be used to make reasonable predictions about plant-soil-water relations. The procedure in Figure 1 illustrates the general relations between seasonal characteristics of the vegetation, its tolerance of drought conditions, and the sources of plant-available water.

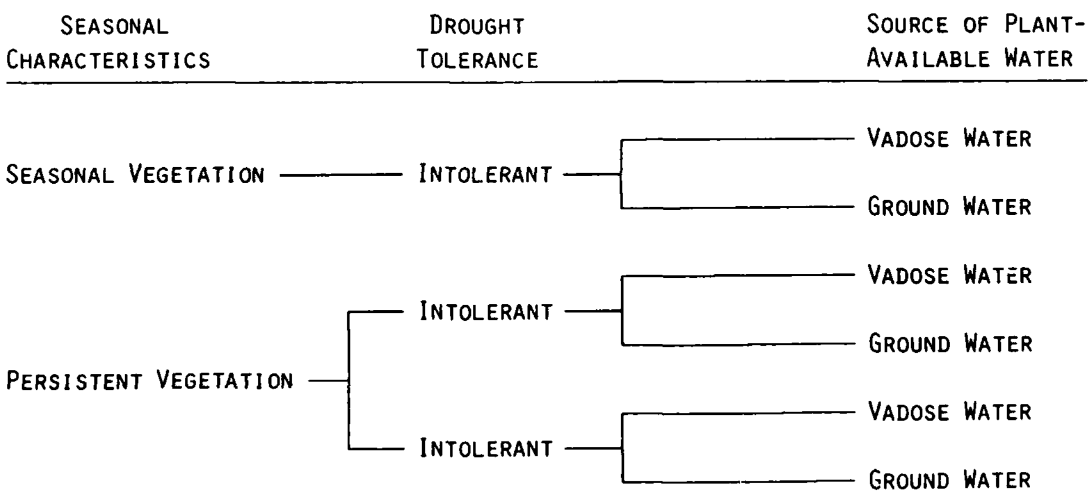



Figure 1. A procedure for evaluating vegetation indicators of near-surface ground water

## Drought-Tolerant Versus Drought-Intolerant Species

Many plant drought adaptations are known. Some of these adaptations can be useful in vegetation analyses using some remote sensing techniques. Many plant species in semiarid and arid regions adjust to the periodic drought through:

a. Seasonal adaptation (completion of annual growth during nondrought periods then senescing at the onset of drought).

b. Morphological adaptations (e.g., reduced leaf area, developing a thick cuticle, producing sclerophyllous leaves or a deep root system).

c. Physiological adaptations (e.g., to minimize water loss or facilitate water uptake at high matric potentials).

d. Phytosociological adjustments (plant spacing).

In the Great Basin of the United States, some cool season grass species , *Bromus tectorum*) avoid summer drought by making rapid growth in the g when soil matrix water is available. These species reach maturity e drought conditions occur. In the northern Chihuahuan Desert of New o, the warm season grass species (e.g., *Sporobolus cryptandrus* and *loua gracilis*) adapt phenologically and produce maximum growth during to late summer, coincident with later summer rains. The drought-erant species (e.g., *Chilopis chilensis*, *Tamarisk* spp., *Populus* spp., spp., and *Carex* spp.) occupy habitats where ground water or surface is readily available.

The use of remote sensors for detecting a vegetative cover can be ely limited by the various adaptive mechanisms that plants use in re-e to drought. For example, the amount of plant cover can be reduced as a t of small leaf size or leaf senescence. The Chihuahuan Desert drought-ant species (such as *Larrea tridentata*) have small leaves that senesce g persistent drought conditions. The shrubs are not detectable at normal graphic scales because of the low amount of ground cover. One would have e imagery scales larger than 1:10,000.

Detection by any given remote sensor is dependent on the reflectance ast between vegetation and the background and the presence of at least inimum detectable amount of vegetation. For a given percentage of vege-e ground cover, different distributions can influence the detection. Our es have shown that the percent of vegetative ground cover present can the spectral characteristics of a given target composed of both soil and ation. The percent cover causing these changes varies with the spectral cteristics of the soil and vegetation. For those spectral regions in vegetation and soil have a large reflectance contrast, a low percentage getative cover in the field of view will have a significant effect on the ned spectral signature. Conversely, when there is a small

AD-A154 053 PROCEEDINGS OF THE GROUND-WATER DETECTION WORKSHOP HELD AT VICKSBURG MISS..(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS ENVIR.. E A DARDEAU 2/2

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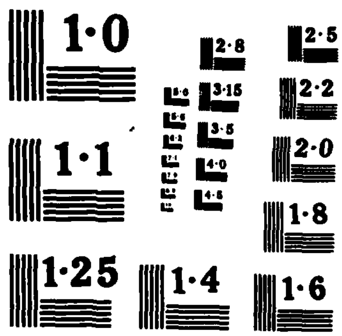
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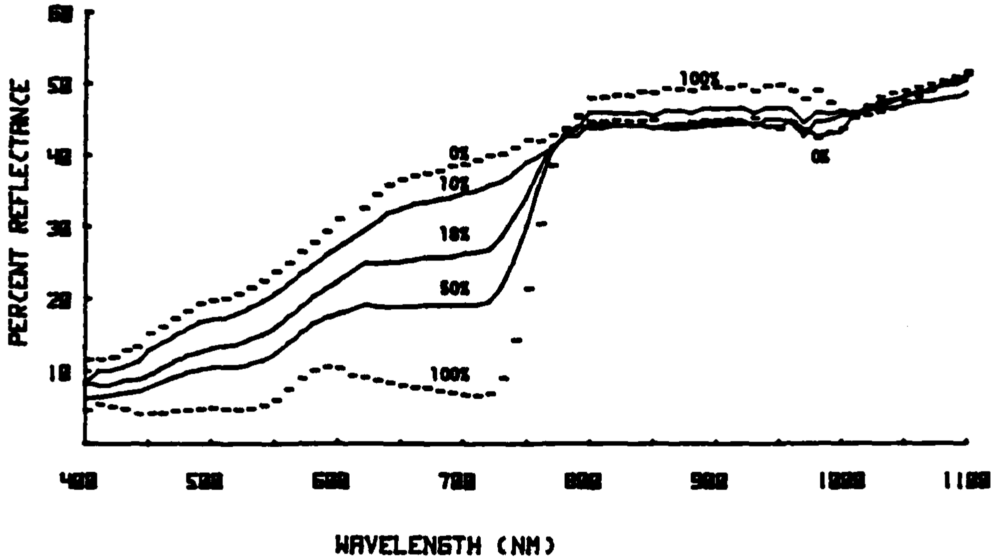
vegetation-soil reflectance contrast, a high percent vegetative cover is needed to significantly affect the combined spectral signature. The minimum amount of green vegetation cover that significantly affects the visible spectral signature of a light-toned sand soil is about 30 to 35 percent. For a dark-toned organic loam soil in the infrared region, the minimum cover is about 12 percent (Figure 2) (Satterwhite 1981).

Plant phenological characteristics must be considered in the task of searching for ground water. Because plants are sensitive to changes in soil moisture conditions, they can frequently be detected by remote sensors only during their maximum growth period. Evaluating the vegetative cover in association with the climatic, soil water, and potential evaporation data improves the predictability of whether vegetation is indicative of a ground-water source. Vegetation patterns can result from the presence of drought-tolerant species. Plants whose maximum growth coincides with periods of plant-available soil water, but which senesce during soil drought, would indicate, as a minimum, presence of vadose water (soil matrix water). These species would be shallow rooted, such as many annual dicotyledons and annual grasses (e.g., *Bromus tectorum*). Species with persistent foliage throughout periods of atmospheric and soil drought would suggest either drought tolerance or the presence of ground water.

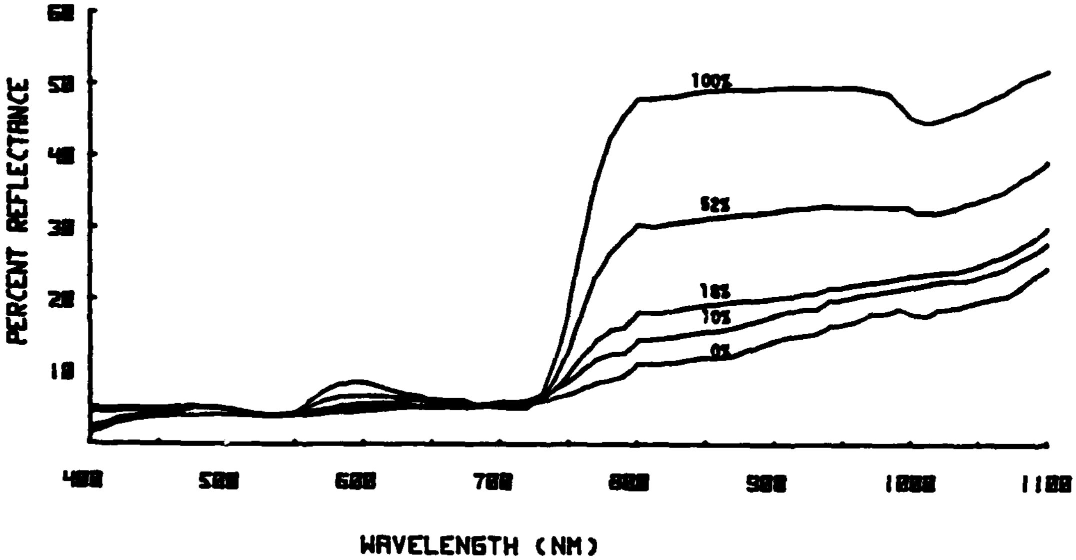
Scale and sensor sensitivity must also be considered. On 1:40,000-scale panchromatic imagery, some shrubs are detectable as small, dark-toned dots that contrast with the light-toned soil background (e.g., the *Sarcobatus* shrubs in Pumpernickel Valley, Nevada, and the mesquite (*Prosopis glandulosa*) shrubs in Tularosa Valley, New Mexico). The canopies of other shrubs (e.g., big sage brush (*Artemisia tridentata*) and shadscale (*Atriplex confertifolia*)) were not detected at this image scale because of their smaller canopy sizes and the lack of contrast between the soil and the vegetation. Vegetation-soil contrast and the percent vegetative cover also determine, in part, the vegetative effect on soil reflectance in the Landsat image.

## Vadose Water Versus Phreatic Water

Determining when the vegetation is an indicator of vadose water and when it is an indicator of either ground water or perched water is a complex problem because the plant can utilize both water sources. Some evidence can be




a. Light-toned sand soil




b. Dark-toned organic loam soil

Figure 2. Reflectance curves for light-toned sand and dark-toned organic loam soils wit. 0 to 100-percent vegetative cover

acquired by evaluating the plant-soil-water relations and using sequential imagery. A general water budget can be estimated from precipitation data and evapotranspiration data; soil texture, depth, and percolation data; depth of soil drying from surface evaporation; soil water estimates; and plant consumptive use estimates. The soil-texture and soil-water relations are used to estimate the potential plant-available soil water (Satterwhite 1980). This estimate, together with climatic data, can lead to an estimation of when the plant-available soil water would be depleted. Continued plant growth and foliage cover beyond this time would indicate either xerophytic or phreatophytic vegetation.

The xerophytic and phreatophytic vegetation could be differentiated by their reflectance and canopy characteristics. Drought-tolerant species often have canopy features (reduced leaf size and canopy cover) that prevent their detection by various remote sensors. The drought-intolerant species can have dense canopies and a high percentage of ground cover that would make them easily detected on remotely sensed imagery. This situation is illustrated on a Skylab 3 color-infrared (IR) image (21-317) over northern Nevada. Big sagebrush (*Artemisia tridentata*) occurs extensively on well-drained, and often droughty, uplands. This vegetation is not shown as having a high IR reflectance. The vegetation occurring on the stream channels (e.g., willow (*Salix* spp.), birch (*Betula* spp.), cattail (*Typha* spp.), and slough grass (*Beckmannia* spp.)) is shown on the image as having a high IR reflectance.

As the water is withdrawn by the plant or lost by surface evaporation, the soil water (vadose water) potential increases. When the soil water is not recharged, the soil water potential increases and eventually the plant is unable to acquire water from the soil. Most semiarid and arid region plants can extract water from the soil at the 20- to 40-bar potential, with some species extracting water at 60 to 80 bars, a much higher potential. Once the plant-available soil water has been depleted, the plant must acquire water from other zones, or it must endure or avoid atmospheric and soil drought. Ground water or perched water in the root zone can be a source of plant-available water. Use of this water depends on the plant's rooting depth, which for some plants has been reported to be 20 m (Meinzer 1927).

Using vegetative indicators of near-surface ground water is contingent on the use of these waters for continued plant growth when soil water is not available. Plants using the ground water should have characteristics (foliage

during the drought period, large canopies, and good ground cover) that enable detection using remote sensing techniques.

## Summary

The vegetative spectral and cover characteristics and their drought avoidance mechanisms will affect the detection of vegetation on remotely sensed imagery. Together, the season of vegetative cover and the anticipated atmospheric and soil drought could suggest the probable locales of plant-available water for the vegetation remaining in the fully leafed-out condition. However, this evaluation should be made with some knowledge of the associated geological conditions that would support this prediction. Additional study is required to:

a. Develop and test reasonable estimates of plant-soil-water budgets for selected semiarid and arid regions.

b. Determine the relation between vegetative cover and plant-available water, particularly when ground water is a source of plant-available water.

c. Evaluate and compare the morphological features of drought-tolerant and drought-intolerant species growing in semiarid and arid environments.

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PROJECTILE PENETRATION TECHNOLOGY APPLIED TO GROUND-WATER DETECTION

by

Dr. Paul F. Hadala*

## Introduction

Several people have suggested that one means of detecting ground water is to fire a projectile into the ground and use onboard instruments to sense the presence of ground water. There are three key factors in this approach to ground-water detection: penetrator survivability, depth of penetration, and the types of sensors and transmitters to use in the projectile.

Survivability refers to the capability of the projectile and its onboard instruments to resist damage or destruction upon impact. As impact velocity increases, the chances of survival decrease. As will be shown later, the state of the art of building hollow (to hold instruments) metal penetrators is such that these devices have not survived at high impact velocities (several thousand feet per second) even in soft soils. Additionally, impacts not perfectly normal to the ground surface cause unsymmetrical loading on the projectile, which can result in the bending and the breaking of the outer case. Just two or three degrees of attack angle (the angle between the projectile's velocity vector and its longitudinal axis) are all that are required to reduce by half the impact velocity at which a projectile will survive.

The second factor, depth of penetration, relates to the maximum depth at which ground-water detection is possible even if all of the other technology problems are overcome. The greatest penetration depth achieved to date by a kinetic energy penetrator is 208 ft. A long slender optimized penetrator was fired into a very soft target (San Francisco Bay mud) by Sandia Laboratories to achieve this record. Since that time, several high-velocity penetrators with impact velocities of about 2500 fps have reached depths of 150 ft in tests at White Sands Missile Range. Shown below is the Sandia empirical formula for high-velocity projectile penetration which these and many other data support.

$$D = 0.0031SN \sqrt{W/A} \, (V_o - 100)$$

* US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

$D$ = depth of penetration, ft

$S$ = soil $S$ number (1 for soft rock, 5 for desert alluvium, and 10 for wet soils)

$N$ = nose shape factor = 1.1 for 9.25-caliber radius head (CRH)

$W$ = weight of the projectile, lb

$A$ = projected area of the projectile, sq in.

$V_o$ = impact velocity, fps; $V_o \geq 250$ fps)

Because of geometry, metals technology, and the need for space to carry a lightweight instrument package, a penetrator has not been built with a $W/A$ value greater than about 15 psi. A penetrator with these characteristics is relatively long and slender and susceptible to damage by oblique impact or attack angle effects.

If $W/A$ is 15 psi, then for soils such as desert alluvium ($S = 5$), the depth of penetration versus velocity relation is

$$D = 0.066\ (V_o - 100)$$

The above formula indicates that a 2000-fps impact velocity is needed to achieve a depth of penetration of 125 ft. As will be shown, the upper limit of impact velocity for projectile survival in $S = 5$ soils is presently about 3000 fps. This limit is based on strength of the best available steels and on maximizing penetrator sidewall thickness (while still leaving some room for payload). The maximum amount of penetration possible with state-of-the-art devices is 190 ft in desert soils. To achieve this depth would require almost perfect (i.e., normal) impact conditions and no rocks or boulders.

State-of-the-art technology is a key point because it limits the depth of penetration, in cases of interest here, to about 200 ft. Therefore, even if all technical questions concerning onboard instruments to detect water and transmit data back to ground surface could be solved, the detection system would be limited to a 200-ft depth.*

The levels of manpower and logistics involved in drilling a 200-ft-deep exploratory hole are comparable to those required to achieve the same hole

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* A shape charge hole-making system has an even more limited depth capacity in the present state of the art. As far as this writer is aware, the world's record is a 52-ft-deep hole made by Los Alamos Scientific Laboratory in alluvium using a 200-lb charge.

with an earth penetrator (EP). More technology, higher skilled labor, and certainly more cost are involved in the use of an EP than with conventional exploratory drilling. The only possible advantage of an EP system over drilling is that of time. However, this advantage is counterbalanced by the fact that a drill hole will provide direct evidence of usable water if present, while an EP can provide only indirect evidence of lesser reliability.

The third factor, sensor type, is one about which very little is known. There are two types of sensors. Direct sensors respond only to the presence of water. While there may be some measurement of this type that can be developed based on chemical characteristics of the compound $H_2O$, there are no geophysical tests that respond only to water. Indirect sensors or indirect measurements are the basis for geophysical ground-water prospecting. Interpretation of the data leads to one of two conclusions: (a) "Water is not present," or (b) "Water is possibly present, but the same measurement could also be indicative of ____________ or ____________ instead of water." Knowing that water is present is not enough. One must determine whether the stratum in which water is present is sufficiently permeable to permit a well to be developed. Ideally, a water-detection penetrator should be capable of collecting data to permit such a determination. Finally, the data must be sent to the local ground surface or to some remote location where they can be used. There are two methods of data transmission: wire communication with the surface and through-the-ground telemetry. Later in the paper, some examples will be given about penetrator instrumentation.

## Earth Penetrator Delivery

Available data indicate that impact velocities of greater than 2000 fps are required to achieve 200-ft penetration. The ranges of impact velocities achievable by the various delivery systems are given in the tabulation below.

| Method | Velocity, fps |
|---|---|
| Artillery delivered | 200 - 500 |
| On-site, gun or rocket | 1000 - 2500 |
| Helicopter drop | 200 - 1000 |
| Jet aircraft - dive-bombing mode | 2000 (?) |

These values indicate that only dive-bombing jet aircraft or gun-fired or rocket-assisted projectiles (fired at pointblank range) can achieve the kind of velocities needed to use a penetrator to investigate shallow groundwater sources.

Sandia Laboratories developed a large recoilless rifle to fire 200- to 400-lb projectiles into earth media (Figure 1). The gun and its support

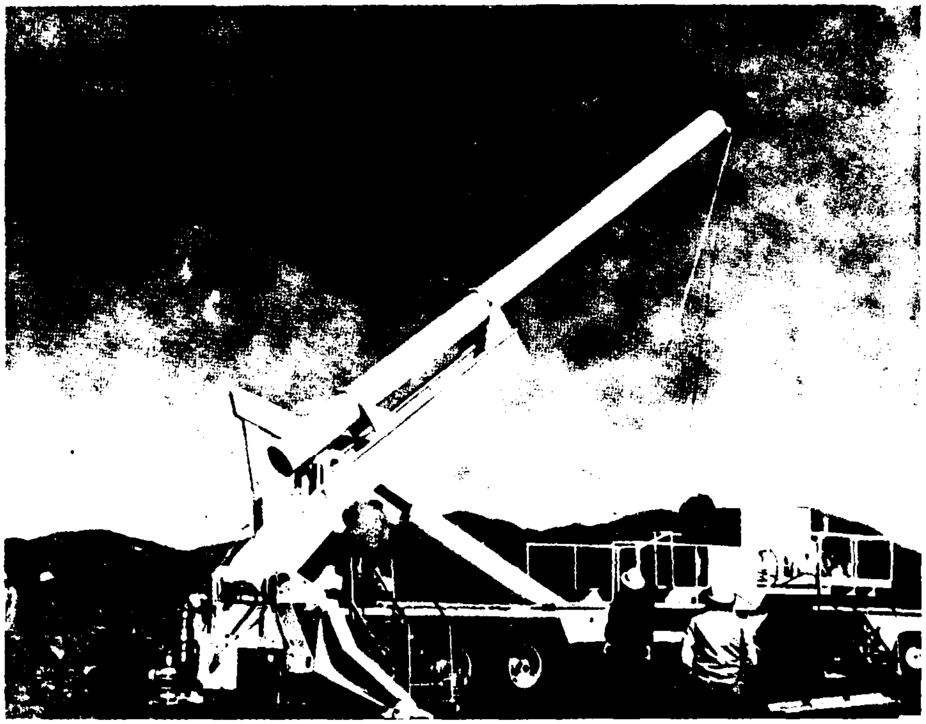

Figure 1. Large recoilless rifle developed by Sandia Laboratories to fire 200- to 400-lb projectiles into earth media

equipment are comparable in size to a large drill rig. While the penetrator firing process itself takes only a fraction of a second, the setup of the device, the loading of the projectile and propellant, and the checkout of instrumentation onboard the projectile takes 2 or 3 days. In this amount of time, a drill rig can set up and drill a 200-ft-deep small-diameter exploratory hole in soil. In rock, the maximum depth would likely be 20 or 30 ft in this same time frame; however, a 2000-fps projectile would achieve only about 20 ft of penetration in rock.

## Projectile Survival

The key technical question limiting EP performance is the survival of the penetrator case and internal components (see Figure 2) during impact with the soil surface, buried boulders, or underlying rock layers. If the penetrator is to make water-related measurements, it must have internal electronic instruments, batteries, and amplifiers. It must also have an onboard transmitter of some sort to transmit the data to the ground surface. For such an instrument to function and transmit data, the case must survive.

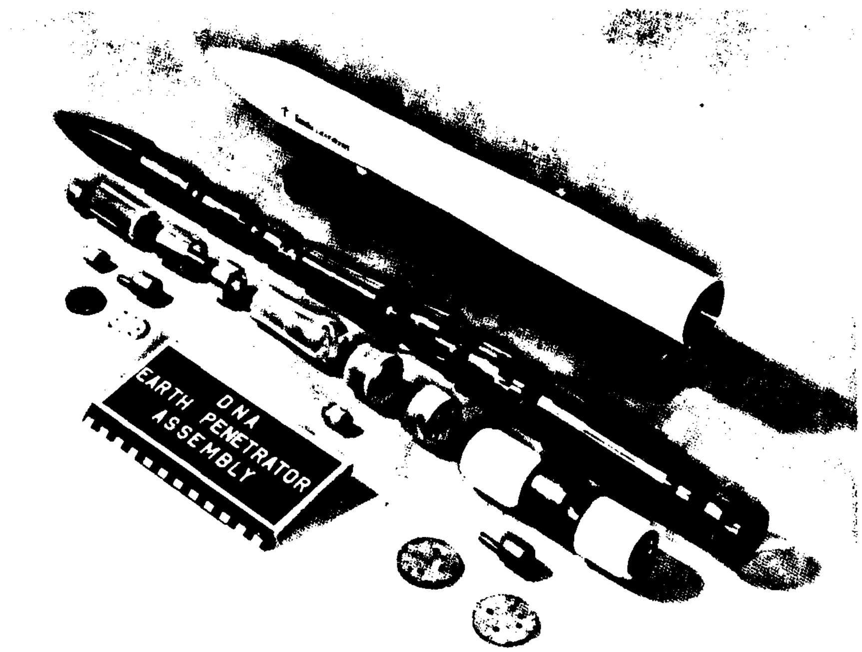


Figure 2. Case and internal components of an EP assembly

The EP shown in Figure 3 failed after impact with a 10-$ft^2$ block of soft sandstone at a 2-deg attack angle and velocity of 1500 fps. This EP was made of a single forging of a very strong, high-fracture toughness steel. Of course, the internal components shown in Figure 2 were also destroyed.

Figure 4 is taken from a state-of-the-art report* on earth-penetrating weapon technology and summarizes much of what has been discussed about

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* Classified reference. Bibliographic material for the classified reference will be furnished to qualified agencies upon request.

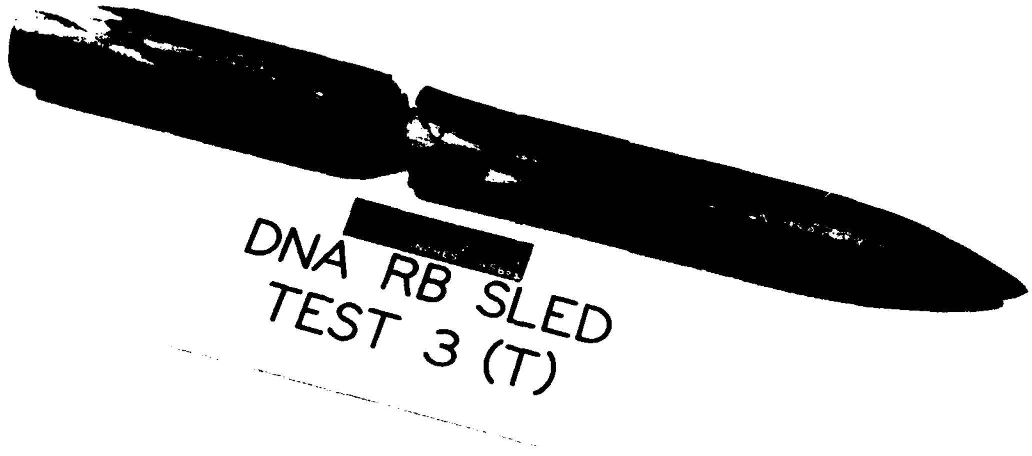


Figure 3. Penetrator destroyed in 100-fps reverse ballistic test against a weak sandstone target

projectile penetration depths and survivability. As shown in the figure, the upper limit impact velocity at which an EP structural outer case will survive an almost normal impact decreases as the soil becomes stronger. This limit is based on extensive empirical data. The depth of penetration lines shown are obtained from the Sandia formula for each condition notated. As previously stated, the survival limit for the water detection application of EPs is 1800 to 3000 fps depending on the type of soil. For optimized projectiles, depths of penetration could be multiplied by about 1.5.

## Survival of Contents

In the state-of-the-art report mentioned above, accelerations and strains on dummy internal components of the projectile shown in Figure 2 were measured. Strains beyond the elastic limit and high-frequency accelerations above 20,000 g's were recorded. This is, to say the least, a difficult

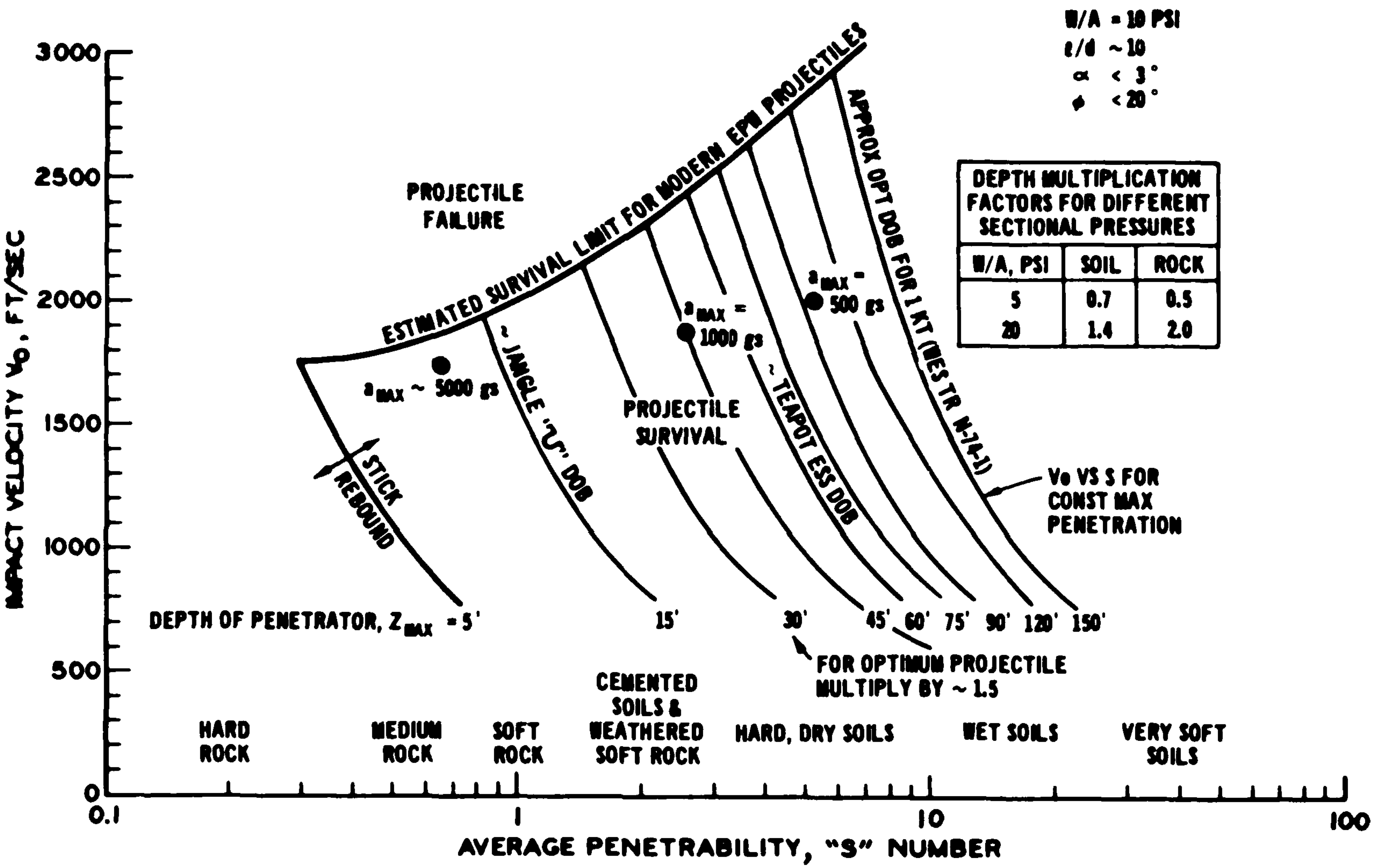


Figure 4. Summary of operational limits on current EP weapon designs imposed by penetration technology

environment in which to keep an electronic instrument payload operational. Much trial-and-error experimentation is required to satisfactorily harden the payload. The terminal delivery vehicle developed by REMBASS (Remotely Monitored Battlefield Sensor System) was carried inside a 155-mm shell (Figure 5). At about the maximum height in the shell's flight, the vehicle is expelled from the back of the shell by a small explosive charge and dropped in a near-vertical trajectory where it impacts the ground. The fins are deployed as shown, and the back section attaches to the ground surface. Separation occurs just ahead of the fins and the nose-body section and continues downward to a depth of 5-10 ft, unwinding a wire connected to the antenna in the back section as it goes down. This projectile carries a seismic noise sensor, batteries, amplifier, and radio transmitter. In repeated trials, the impact shock-damaged radio crystals.* By a combination of analysis and trial-and-error testing, crystal mountings and crystal natural frequencies were changed to reduce the failure rate. This is the only projectile of which the writer is aware that performs any type of sensor mission, and it is limited to about 10 ft of penetration at low-impact velocity.

## Sensors

Assuming that the projectile survives the impact and achieves the desired depth of penetration, then, after the high-shock ride, the contents must function to detect water. What type of sensors can be employed for this purpose? Very little work has been done to answer this question, but more than [illegible] detection method should be electrical (i.e., resistivity) or chemical (i.e., some chemical that reacts with water, absorbs water, or is dissolved in water in a way such that an electrical signal is produced by a device that measures the change in the mass or volume of the chemical or the heat of reaction). For either of these methods to work, there must be an open channel into the interior of the projectile for wires from the resistivity electrodes or to permit the flow of water into the chemical reaction chamber. Such holes seriously weaken the projectile case unless they are at the back end of the projectile.

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* Although impact with the ground damaged the payload, the shock of being fired from a 155-mm gun did not.

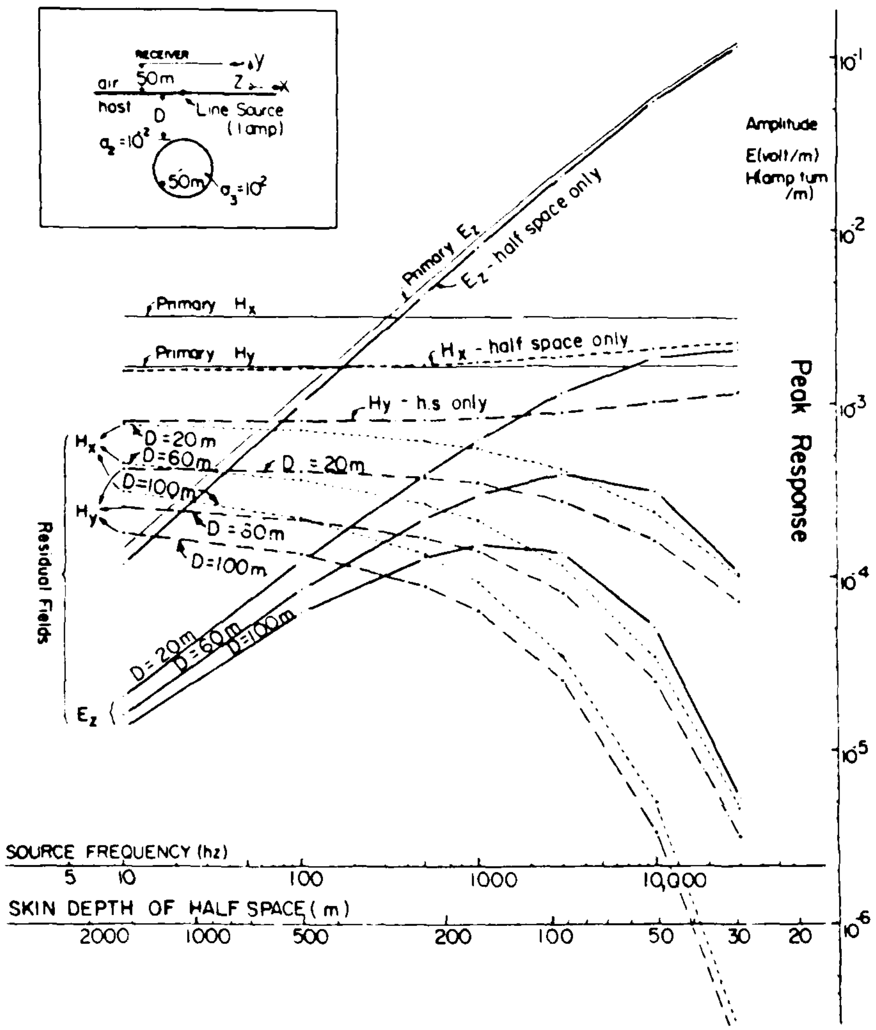


Figure 2. Peak amplitude response as a function of frequency for a circular cylinder in a half-space at three different depths, 20, 60, and 100 m. Skin depth of the half-space is shown along the frequency axis (from Won 1981)

Obviously the state of the art for this technology is far from complete. Needless to say, further theoretical development in wide band frequency responses of realistic earth conditions, especially related to ground-water aquifers, is needed as well as advancements in equipment and experimental schemes. Current capability is strictly limited to ground measurements; theoretically, however, the potential is there for accomplishing airborne measurements with similar technology. An obvious advantage to spectral profiling is the ability to classify any significant anomalies in terms of their subsurface distributions. Physically, an anomaly caused by a large and deep structure

Major obstacles in the development of continuous-frequency EM systems are: (a) poor theoretical understanding of wide band induction phenomena and (b) lack of instrumentation for field data collection and processing. The theoretical understanding of wide band diffraction as applied to EM energy is improving but still quite primitive.

Won and Kuo (1975a, 1975b) formulated a generalized EM diffraction theory involving more than two media (for example, air, rock, or water), each having an arbitrary electrical conductivity, dielectric permittivity, and magnetic susceptibility. Won (1980) tested the theoretical results through experimentation in a scaled laboratory environment using a swept-frequency EM system. He simulated conductive earth with saline water and various targets with a thick graphite slab. The experimental model results, which were in qualitative agreement with theoretical results, provided impetus for continuing the development of this technology.

The limited theoretical and laboratory experiments led to the development of a prototype field system. A block diagram of this system is shown in Figure 2. It is functionally divided into transmitter, receiver, system control, data acquisition, and playback components. Specific facts concerning this system are as follows: (a) it operates in transit with a loop-loop transmitter/receiver configuration; (b) it transmits a logarithmic sweeping harmonic signal from 500 Hz to 100 KHz; (c) the receiver measures secondary field amplitudes and phase spectra of the return signal; (d) data are displayed as a continuous spectral profile with distance, which effectively gives a conductivity cross section of the earth's subsurface; and (e) spectral profiles in the frequency/distance domain can be interpreted very similarly to reflective seismic profiles in the time/distance domain, providing ease of interpretation of the results.

## Summary

The field data obtained thus far are encouraging. All major anomalous spectral features in the data have been recognized and identified with available ground truth data as caused by either geologic or cultural origins. In addition, preliminary results based on theoretical studies of a horizontally layered earth indicate that there is a strong correlation between a given geologic model and its electromagnetic spectral profile.

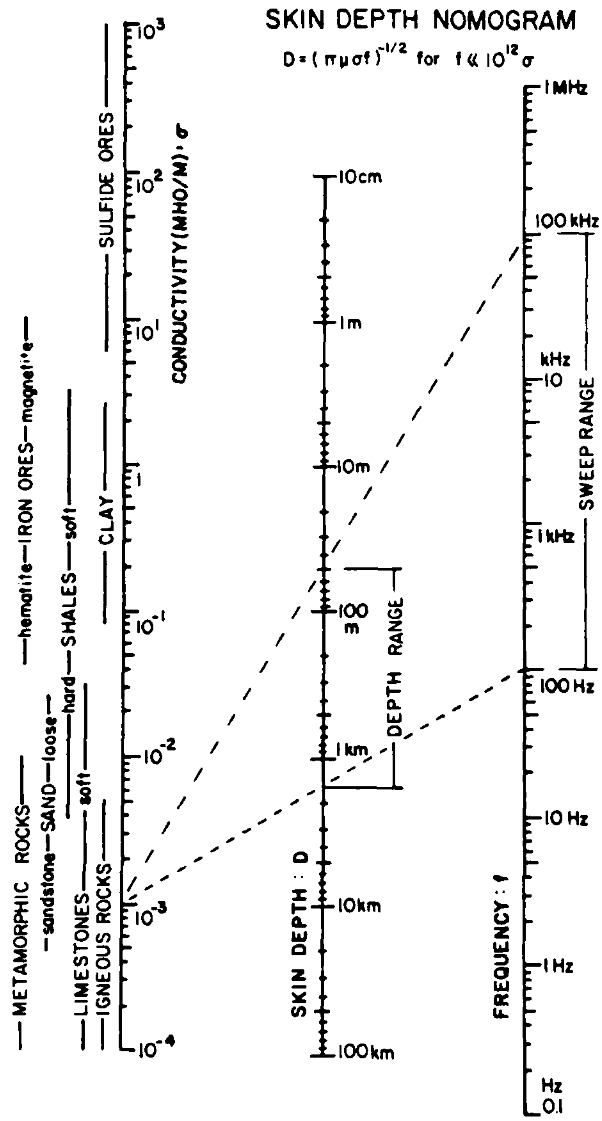


Figure 1. Relation of source frequency, ground conductivity, and depth of penetration. For example, if the source frequency sweeps from 100 Hz to 100 KHz in a typical igneous rock area, the depth of exploration (skin depth) ranges from about 40 to 1500 m (from Won 1981)

drawback of these multiple-frequency systems was that each frequency required a separate operation; thus, without introducing a frequency multiplexing or power switching scheme, such a system could not be used in a dynamic mode. This would eliminate these techniques as ground mobile or airborne reconnaissance tools. The swept-frequency technique would provide the multiple-frequency measurement capability over a very short time frame, thus allowing the airborne reconnaissance role.

methods conducted at North Carolina State University, Raleigh (Won 1981), sponsored by the U. S. Army Research Office. Dr. Won's work provides an overview of the character of emerging long-wave EM energy theory, equipment, and methodologies that are available for subsurface exploration.

## Concepts

EM exploration employing single frequencies up to the radio frequency bands has been used for some time, primarily as an induction method for geophysical surveying in the mining industry. This technique utilizes the changes in electrical conductivity of specific mineral deposits as a means of detecting their presence. The single-frequency radio techniques involve the propagation of a time-varying low-frequency EM field in and over the earth.

Ideally, any exploration survey technique would not only locate an object but also provide some additional information on its character and geometry. Thus, the development of an EM method that can more rapidly and economically map three-dimensional subsurface variations and conditions should be pursued. These variations can be due to mineral deposits, ground water, or tectonic structures causing changes in the electrical properties of the subsurface materials.

Dr. Won's approach is based on the assumption that a swept-frequency or variable-frequency EM method could provide both deep penetration and high vertical resolution in a single exploration device. The depth of penetration that can be achieved with EM devices is determined mainly by the frequency of the energy transmitted and the conductivity of the subsurface materials. This relation is shown in the nomogram in Figure 1. Applying swept-frequency techniques, therefore, is really equivalent to doing a depth sounding at a given point. By making the device mobile, either on the ground or in an aircraft, and obtaining the depth soundings as a function of time and space, a three-dimensional methodology could be achieved.

The idea of using multiple-frequency sources in EM surveys is not totally new. Work was accomplished by Ryu, Morrison, and Ward (1972) using 14 discrete frequencies between 200 Hz and 10 KHz to explore for ground water in the Santa Clara Valley, California. Similarly, Ward et al. (1974) and Ward, Pridmore, and Rijo (1977) used 14 discrete frequencies between 10.5 Hz and 86 KHz to explore a sulfide mineral deposit in Ontario, Canada. The

full potential has not yet been demonstrated.

The ground survey systems provide more direct measures of the presence of water because of their means of measurement. Seismic refraction techniques infer the presence of ground water through the velocity of compression waves moving through the earth. Saturated alluvial materials will have a characteristic compression wave velocity that is representative of the velocity of compression waves in water, while unsaturated materials will generally have a different velocity. Resistivity can be used to infer the presence of water through changes in the measured subsurface conductivity because saturated materials have a much higher conductivity and lower resistivity than dry materials. The GPR detects water because wet materials have a much higher dielectric constant than dry materials, and the water table creates a highly reflective surface for the radar energy transmitted into the ground. Loop-loop electromagnetic technique also operates on the principle of electrical conductivity of the materials. While these techniques do provide a more direct way of detecting the presence of water, they are by nature much slower and more expensive to use than the aerial techniques. Refraction and resistivity techniques, for example, require the use of large lengths of cable and equipment to survey an area and are fairly labor-intensive.

Essentially, the technology of today consists of the alternative capabilities of doing very general, large area, indirect surveys through satellite or aerial remote sensing techniques or, in the other extreme, doing more direct local surveys on the ground using geophysical techniques. Neither provides the capability desired for the military community. An aerial technique that would provide a more direct measurement with depth would be a significant enhancement in capability and would move closer to the operational capability desired for the military.

## Objective

The objective of this presentation is to briefly discuss an emerging technology that could provide an enhanced ground-water survey capability in the future. As such, this demonstrates that technology is advancing. New concepts that have considerable promise for enhancing ground-water survey capabilities should be investigated in detail. This paper is based on Dr. I. J. Won's research on swept-frequency electromagnetic (EM) exploration

OVERVIEW OF ADVANCED ELECTROMAGNETIC TECHNIQUES FOR GROUND-WATER EXPLORATION

by

Dr. Lewis E. Link, Jr.

## Introduction

The ability to rapidly survey large areas to detect the presence and character of ground-water resources is important for any military operation in arid regions. A wide variety of potential techniques exist; however, none provide the desired quantitative capability for military applications. Existing aerial and satellite remote sensing systems can provide information relevant to groundwater resources over large areas. Inference of ground-water conditions can be made through (a) delineation of subsurface geologic conditions through their surface expression, (b) lineations that indicate fracture zones, or (c) vegetation indicators. By examining imagery acquired at appropriate times, some judgment can be made with respect to the presence of an aquifer that could contain ground-water resources. However, these systems cannot be used to directly infer the actual presence of ground water, other than perhaps through some of the vegetation indicators. Their major advantage is that they provide a rapid, relatively low-cost survey of very large areas. Their major disadvantages are that ground water cannot be sensed directly and that only the presence of a water trap or the conditions favorable for the accumulation of ground water can be inferred through terrain surface conditions observed on imagery.

A variety of existing techniques based on ground survey systems provide more direct measures of the presence and sometimes the character of ground-water resources. These techniques include seismic refraction, electrical resistivity, loop-loop electromagnetic surveys, and ground-penetrating radar (GPR). The seismic refraction and resistivity techniques that have been used in geophysical prospecting have also proved to be successful methods for locating ground water to depths of hundreds of feet. In military operations, they are not amenable to application by untrained individuals. Interpretation of both refraction and resistivity data requires sophisticated analysis techniques and significant training on the part of the interpreter. The loop-loop electromagnetic and GPR techniques are relatively new methods, and their

determined induction well log record at the same location. The exciting aspect of this TDEM procedure is that as many as 20 soundings per day could be conducted under favorable conditions. The TDEM method, however, still has the same nonuniqueness as any other method used to determine resistivity as a function of depth.

direct ground-water detection. Direct ground-water detection, however, must be viewed as a long-term goal.

There are several EM techniques such as magnetotellurics and various types of loop-loop, dipole-dipole, loop-dipole, etc., methods that can be used to determine resistivity or conductivity as a function of depth. Compared to the electrical resistivity techniques discussed previously, these EM techniques can be more rapid and less logistically cumbersome, and they do not require surface contact.

One of the most promising of the emerging technologies is the time-domain electromagnetic (TDEM) method. In the TDEM method, a very broad bandwidth EM signal is input to the ground, and, because the signal is transient (i.e., not a continuous wave source), very high power levels are possible. The return signal is interpreted to give resistivity as a function of depth. Figure 1 shows an interpreted TDEM record and compares it to an independently

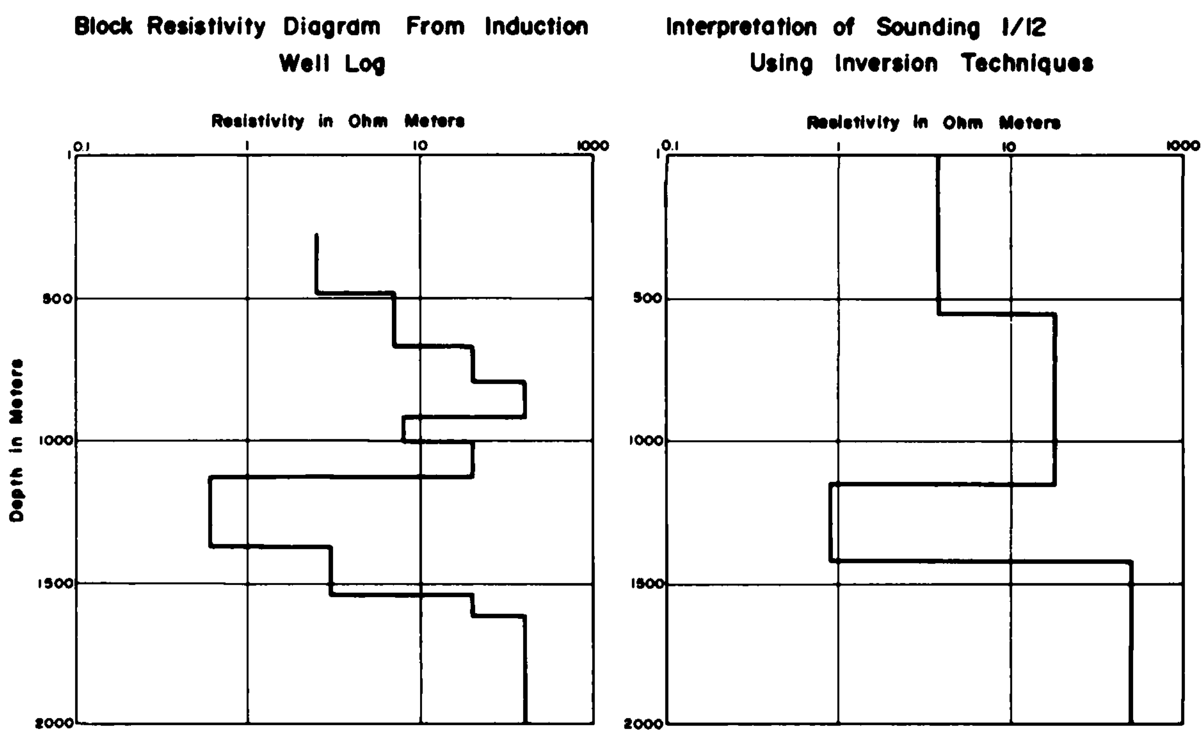


Figure 1. Comparison of well log resistivities and the inverse interpretation of TDEM sounding 1/12. The similarities both in equivalence of resistivity and layer thickness is quite remarkable (from Harthill, N. 1976. "Time-Domain Electromagnetic Sounding," Institute of Electrical and Electronic Engineers, Transactions on Geoscience Electronics, Vol GE-14, No. 4 (Oct), pp 256-260.)

EMERGING TECHNOLOGY: GEOPHYSICS

by

Dr. Dwain K. Butler

In emerging geophysical technology, new or adapted techniques are sought to detect or determine subsurface indicators of the presence of ground water: stratigraphic indicators, structural indicators, aquifer properties. A few techniques that hold promise for future application to ground-water exploration include:

a. Seismic reflection techniques to determine $V_p/V_s$ as a function of depth.

b. Induced polarization applied to ground-water detection.

c. Controlled source audio-frequency magnetotellurics.

d. Time-domain electromagnetic methods.

e. Standard electromagnetic methods applied to ground-water exploration (i.e., loop-loop, dipole-dipole, loop-dipole.

An advancing technology is the use of seismic reflection methods to determine various types of reflection cross sections. The state of the art in determining both compression ($V_p$) and shear-wave ($V_s$) velocities from single primary reflection panels (collection of all geophones receiving signals from a single source location) is rapidly advancing. Thus, both compression and shear-wave interval velocities can conceivably be determined from a single "split-dip" spread setup, though different sources might be required to generate separate compression and shear-wave reflection panels. From this procedure, $V_p/V_s$ ratios would be determined as a function of depth and, due to the fact that shear-wave velocities are generally much less affected by water saturation than compression-wave velocities, the $V_p/V_s$ profile should be highly indicative of the occurrence of ground water. Because only a single reflection spread setup is required, the logistical complexities associated with the continuous reflection profiling procedure are avoided.

If there is ever a device that even comes close to the "black box" water detector ideal, it will likely be an electromagnetic (EM) device. There are numerous EM techniques ranging from near-DC induction techniques to GHz wave-propagation techniques. Hopefully, some innate property of the aquifer system will be amenable to interrogation or probing by an EM technique and allow

If somebody went into a major technology development program in this area and was willing to put a lot of money and time into it, I'd say you could develop a system that could air-deliver a projectile and get it into the ground at a depth of 200 ft (as long as you didn't hit rock or surface boulders) and could receive data from it. But you'd be investing many millions of dollars to get that.

In projectile penetration technology, we've got essentially two ways to go in R&D. We can do some things with large finite-difference hydrodynamic codes, such as calculating the forces on the projectile during impact, and the structural response of the projectile. This only gets us in the right order of magnitude; it doesn't tell us much of anything about the details that are going to kill the components of the projectile. In the laboratory, researchers must build full-scale projectiles and try to make them survive after firing into artificial targets that are about as hard as the field targets. When the EP survives in that environment, you take it out to the field and start doing full-scale field tests. In order to find out what went wrong with your projectile in the field test and learn from it, you've got to dig it up. If you're getting it down 200 ft, that's a 200-ft-deep, large-diameter cased shaft that you've got to dig into the ground for men to get into it to recover the projectile. Then you can do a post-mortem on the EP and find out why it failed and fix that item. Next, you go back into some more impact tests or reverse ballistic tests in the laboratory and continue the trial-and- error process.

Developing an EP is an expensive, time-consuming process with no guarantee of success.

Q. Why don't you just probe the hole left by the projectile?

A. You can't guarantee the hole will stay open. Basically, my experience with deep penetration of dry soils at Main Lake Range at Tonopah Test Range, Nevada, has been that only the top third to half of a hole will remain open. In other words, when the smoke clears you rush back in and try to start pushing rods down the hole, and you don't hit the penetrator. The way we determine where those penetrators are is by mining down in shafts and picking them up. If you get lucky and run through a water-bearing stratum, the hole certainly won't stay open.

Q. I think the point is, as mentioned before, that this is not a short-term solution, but it certainly should not be ignored for long-term research, as far as looking at it as something that is useful.

A. There is a very fundamental problem in converting kinetic energy to strain energy.

Q. Has there been any experience with making measurements of soil conditions as the penetrator is going down?

A. There has been. The deceleration of the projectile has been recorded on the way down. And after the EP has come to rest you can play back the whole history of what happened on the way down via telemetry. If you could make resistivity probes survive on the outside of the projectile, you could get a continuous resistivity pattern.

Let me tell you about another problem with high-velocity penetration. We've done metallurgical examinations of the surface of penetrators that have gone deep in the soil with high-impact velocities. The surface of the metal melted. A thin skin about a couple thousandths of an inch thick on the recovered penetrator had melted and recrystallized. The 8in.-diam penetrator was measured and found to be 0.02 in. smaller than what it was before it went into the ground. By carefully probing the sides of the hole with a magnet, we were able to recover small pieces of steel. Metallurgical examination proved these pieces had been melted and had come off that penetrator. Getting something to survive that high temperature environment and take a measurement on the way down is extremely difficult. Friction on the side of that projectile is sufficient to melt steel when you have sufficient velocity to get the kind of depth you need.

## Question-and-Answer Period

Q. What do you think are the possibilities of using static penetrator technology for ground-water detection down to the 50- to 100-ft depth range?

A. In geotechnical exploration, we do it routinely; it's called the Dutch cone penetration test. Some people have adapted this cone to measure the resistivity of the soil as a function of depth, as well as the point and skin friction resistance of penetration. From those three measurements, you can get a pretty good idea of whether you're going through a sand or clay without getting the sample back to the surface. Practically speaking, you've got to have a lot of mass on the surface for reaction of the hydraulic system that pushes the cone into the ground. I don't know of any penetration tests deeper than 100 ft. You can run one of these tests to a depth of 100 ft faster than you can drill, but you can't be certain that there's any water down there. All you know is the resistivity.

Q. Will static cone penetration tests go through rock?

A. No, they will not. They will go around small rock. The rod will bend and go around it.

Q. There's a family of runway-cratering munitions that are parachuted and then rocket-fired to penetrate a half-metre of concrete and reinforcing and over 2 ft of crushed rock without destroying the fusing, so there are other penetrating techniques. Secondly, I can envision a scenario where a location of interest can be overflown but is inaccessible to a drill.

A. I can envision that, too.

Q. So, what I'm suggesting is we haven't invented the right thing yet, but we should not summarily dismiss the concept.

A. People have looked at combination shape charge-kinetic energy follow-through penetrators as a means of doing the job. This is what is involved in the cratering munitions just mentioned. These munitions can't achieve the depths we need (200 ft) either. Basically, achieving depth with an EP is just a matter of providing enough kinetic energy; an awful lot of kinetic energy is required to get more than 200 ft of penetration. Making the EP survive the sudden conversion of the kinetic energy to strain energy isn't within the state of the art at energy levels needed to go that deep, regardless of the way you package the kinetic energy.

An alternate to onboard measurement would be for a ground team to probe the hole left by the EP. Experience has shown that such holes rarely remain open to the full depth of penetration, so this is not a high reliability option.

If an onboard sensor successfully obtains data, the next problem is to transmit that information to the surface. There are two ways to do this. One is a hardwire system, such as used by the REMBASS terminal delivery vehicle. The other is by through-the-ground telemetry. Sandia Laboratories has had some experience with this. Ground telemetry requires the placement of a receiving antenna on the ground surface in the immediate vicinity of the impact point.

## Summary and Conclusions

Some key points about penetration mechanics and experience with EP tests that bear on the problem of water detection with earth penetrators are:

a. Impact velocity greater than 1000 fps is required for deep penetration.

b. Maximum depth achieved by an earth penetrator is 208 ft.

c. Survival is doubtful in rock or boulders.

d. Penetration to depths of 50 to 100 ft in dry soils is practical.

e. High failure rate for internal electrical and mechanical components occurs due to impact shock.

f. Equipment and time required are greater than to achieve the same depths by conventional drilling methods.

Based on the available data, present metal technology prevents the achievement of depths greater than about 200 ft, even in the softest soil. Thus, an EP ground-water detector development program, even if it were to overcome the serious obstacle of case survivability and internal component performance, would only work at those depths where exploratory drill holes can be accomplished with roughly the same level of effort.

Therefore, EP ground-water detectors should not be pursued, because they are high-risk, limited payoff items.

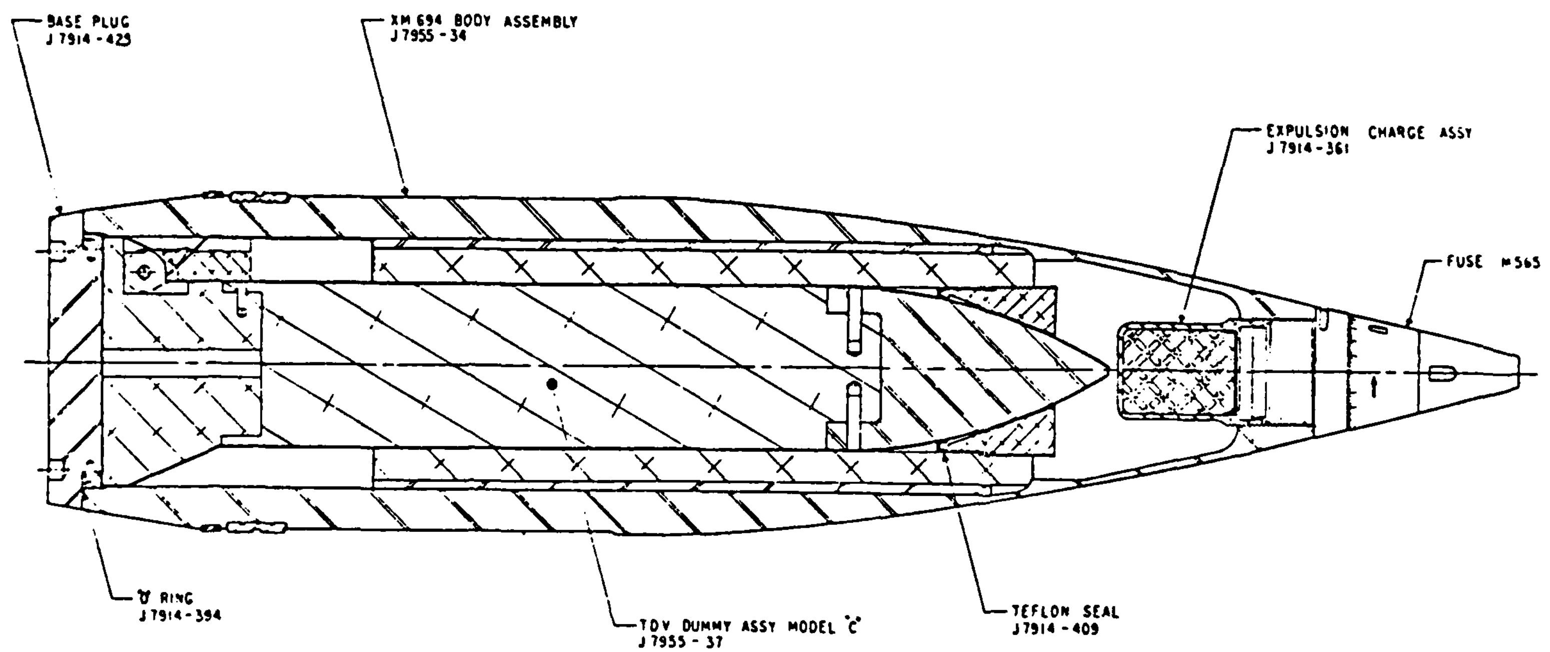


Figure 5. Terminal delivery vehicle carried inside a 155-mm shell

will be a broad feature in space and will be represented by the lower frequencies of the energy transmitted and measured; an anomaly caused by a small shallow structure would be measured as a narrow feature in space and would be represented by the higher frequency data obtained. This is a unique feature of the swept-frequency or continuous-frequency EM concept and is one of the major reasons why, along with the ease of interpretation of the data, this technique holds considerable promise for the future.

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# GEOLOGIC CONSTRAINTS ON GEOPHYSICAL SURVEYS FOR GROUND-WATER EXPLORATION

by

John H. Shamburger*

For a number of years, geophysical techniques have been used successfully in ground-water investigations to locate and delineate aquifers. These techniques include electrical resistivity, electromagnetic, seismic, gravity, and magnetic methods, either solely or in combination. The degree of success attained in a geophysical survey is site specific because of the effects of geologic conditions on both the applications (depth of investigation) and accuracy of the data interpretation. Geologic features, such as structure, stratigraphic relationship, lithology and physical and engineering properties, sedimentary sequences, and surface and paleo-weathering effects, are known to limit or enhance the application of geophysical exploration techniques.

Because of the limited time, my talk will cover only seismic refraction. As you know, seismic surveys are based on the measurement of the velocity distribution of artificially generated seismic waves in the earth's crust. The velocity of the seismic waves depends on the density, elasticity, and composition of the subsurface geological formations. The velocity is usually lowest in unconsolidated materials or soils and increases with the degree of consolidation or cementation.

Before we discuss some of the geologic constraints on seismic refraction, I want to define the nomenclature of geologic conditions in ground-water flow, which are aquifer, aquiclude, and aquitard.

a. An aquifer is a geologic formation or stratum with voids or pores containing recoverable water that can be used as a source of water supply.

b. An aquiclude is a geologic stratum so impervious that, for all practical purposes, it completely obstructs the flow of ground water (although it can be saturated with water itself) and completely confines other strata with which it alternates in deposition.

c. An aquitard is a geologic stratum of a rather impervious and seniconfining nature that transmits water at a very slow rate compared to an aquifer. Over a large area of contact, however, it may permit the passage of large amounts of water between adjacent aquifers which it separates.

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Some strata are good aquifers, and, in contrast, others are poor. To be a good aquifer, a stratum must have interconnecting openings or pores through which water can flow. This characteristic depends upon the composition, origin, and relation of the grains or particles and associated pores of the strata; the relative position in the earth's surface; and exposure to a recharge source and other factors. Generally, the best aquifers are unconsolidated coarse-grained soils (sands and gravels). Coarser grained sedimentary rocks, such as conglomerates and sandstones, are often good aquifers; however, their potential as aquifers is dependent upon cementation and fracturing. Other sedimentary rocks (limestone, dolomite, etc.) can be good aquifers, provided that solutions along fractures have developed voids for water to accumulate. Metamorphic and igneous rocks provide sources of ground water only if they have undergone sufficient stress or weathering to form openings or porous residuum for water to flow. Some lavas, especially viscous basalts, can contain good to excellent aquifers between successive flows.

The three general types of aquifers (unconfined, confined, and perched) are illustrated in Figure 1. An unconfined aquifer is one that does not have a confining layer or aquiclude overlying it. A confined or artesian aquifer

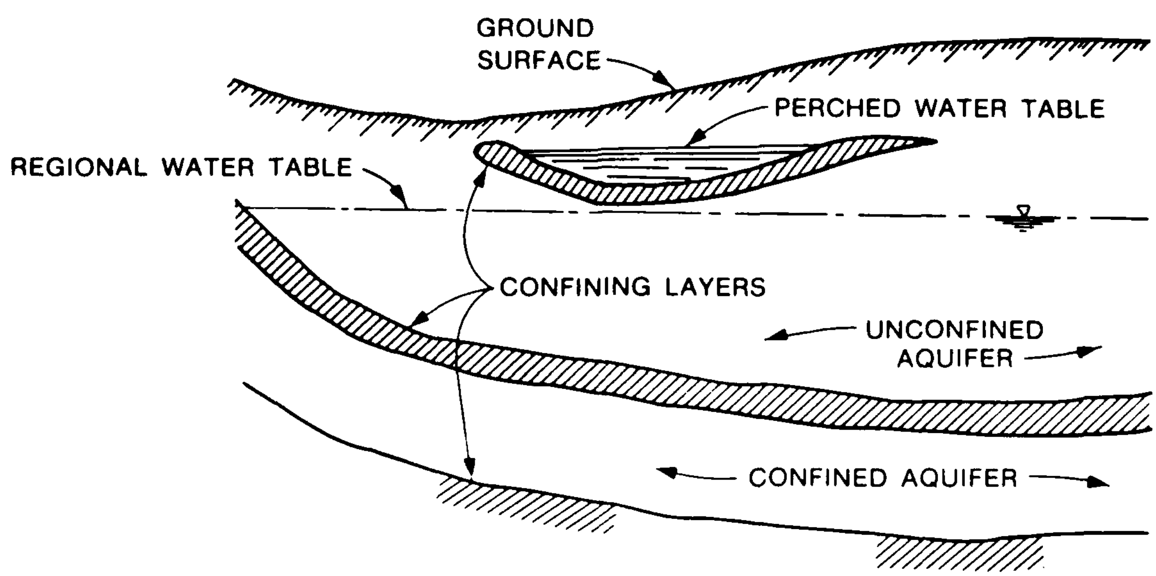


Figure 1. Three general types of aquifers

has overlying and underlying confining layers. A perched aquifer is formed where layers or lenses of relatively low-permeability material trap the downward-moving water above the regional water table.

Many geologic processes have caused heterogeneous conditions that affect the travel time curves and present interpretation problems. Two geologic conditions are troublesome to use in interpreting subsurface conditions from seismic data. I might add that these conditions are not uncommon.

The first one is referred to as velocity inversion, which occurs where the velocities in the layering sequence of soil and/or rock do not increase uniformly with depth (Figure 2). Layer 1 has a lower velocity than layer 2

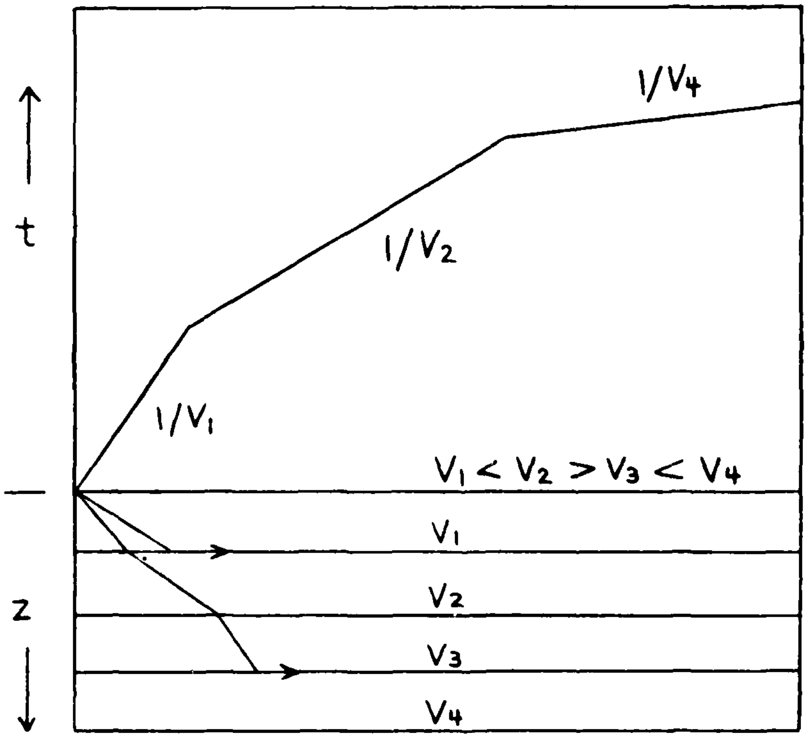


Figure 2. Example of velocity inversion

or layer 3, and layer 3 has a lower velocity than layer 2 or layer 4. The resulting effect will be an incorrect inference of depth to layer 4 because the thickness of layer 3 will be miscalculated.

The second condition, a blind zone (Figure 3), is a three-layer stratigraphic unit in which the seismic velocity increases with depth. However, the middle layer is too thin to act as a reflector, and the depth to a reflector below the thin layer will be miscalculated.

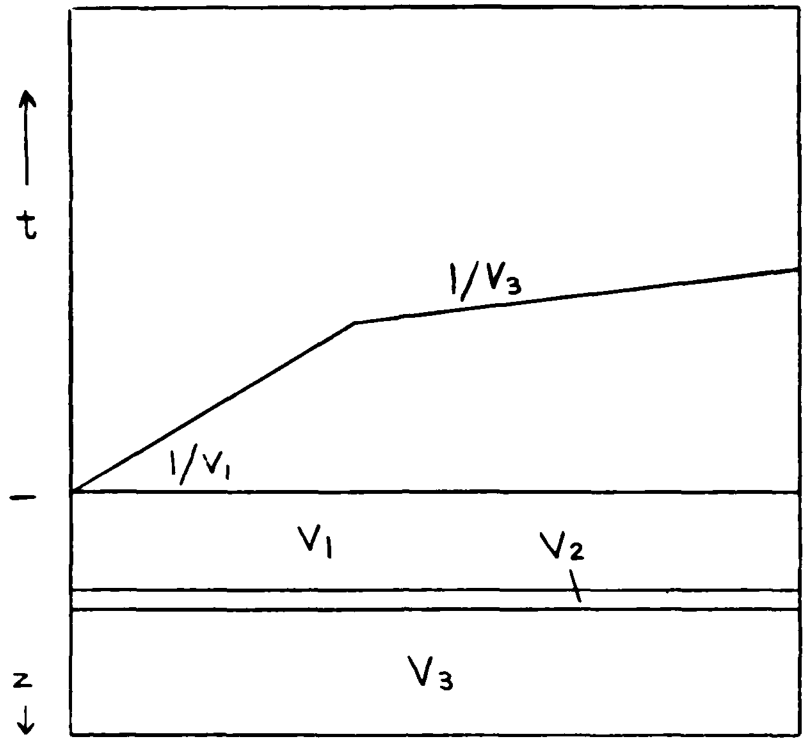


Figure 3. Example of a blind zone

A good example of these conditions occurs at Rocky Mountain Arsenal (RMA) near Denver, Colorado, where a seismic refraction survey was performed in August 1979 as a part of a ground-water contaminant migration study. The overall purpose of the study was to stop contaminants in the alluvial aquifer from crossing the arsenal boundary. This containment was to be accomplished by constructing a slurry trench to block ground-water flow, installing wells in the alluvial aquifer up-gradient of the trench to pump the ground water to a treatment plant, and recharging the aquifer down-gradient of the trench with the treated water through a series of wells.

Figure 4 shows a shallow profile near the northern boundary of RMA with two geologic units: the Pleistocene alluvium and the Denver Formation. The alluvium can be roughly divided into the upper clays, silts and fine sands, and underlying sands and gravels, while the Denver Formation consists of layers of varying thicknesses of clay shale, silt/siltstone, and sand/sandstone. A slurry trench was to be constructed through the aquifer and anchored in the Denver clay shale.

The purpose of the seismic survey was to identify the depth to the water table and the contact between the alluvium and the Denver Formation. These

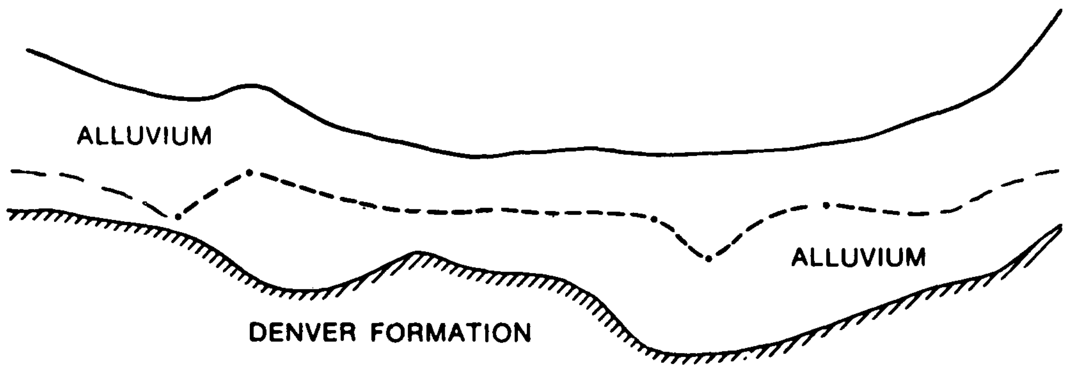


Figure 4. Shallow profile near the northern boundary of Rocky Mountain Arsenal

data were needed to plan the length and depth of the proposed slurry trench and to assist in determining the quantity of water that had to be treated. If the survey was successful, the number of borings could be reduced and a more accurate geologic profile constructed. Another purpose of the survey was to identify the contact between the Denver Formation and the underlying Arapahoe Formation for stratigraphic correlation and to determine if water-bearing sand layers could be detected.

Analysis of the time-distance plots revealed a two-layer refraction system along the northern boundary (Figure 5). The P-wave velocity of the near-surface or upper layer was 630 to 1200 fps, while the lower or second layer ranged from 6000 to 7000 fps. Depths along this seismic profile ranged from 8 to 14 ft. This refractor surface in the alluvium correlates closely with the contact between fine sands, silts, and clays overlying the coarser sands and gravels, as depicted on the geologic cross section. In some places, the coarser material was well cemented with calcium carbonate, which could also increase the P-wave velocity. The alluvium-Denver contact did not show up as a refractor surface because a significant velocity contrast did not exist. Additionally, the velocities did not increase with depth, indicating that the material of the Denver Formation immediately below the partially cemented sand and gravel in the alluvium had a lower velocity and was not detected. Even more critical than not locating the alluvium-Denver contact, the water table was not detected; therefore, based on the seismic interpretations, an aquifer did not exist.

We ran extensions to locate the Denver-Arapahoe interface (250-300 ft below the ground surface) and saturated zones within the Denver. Points on

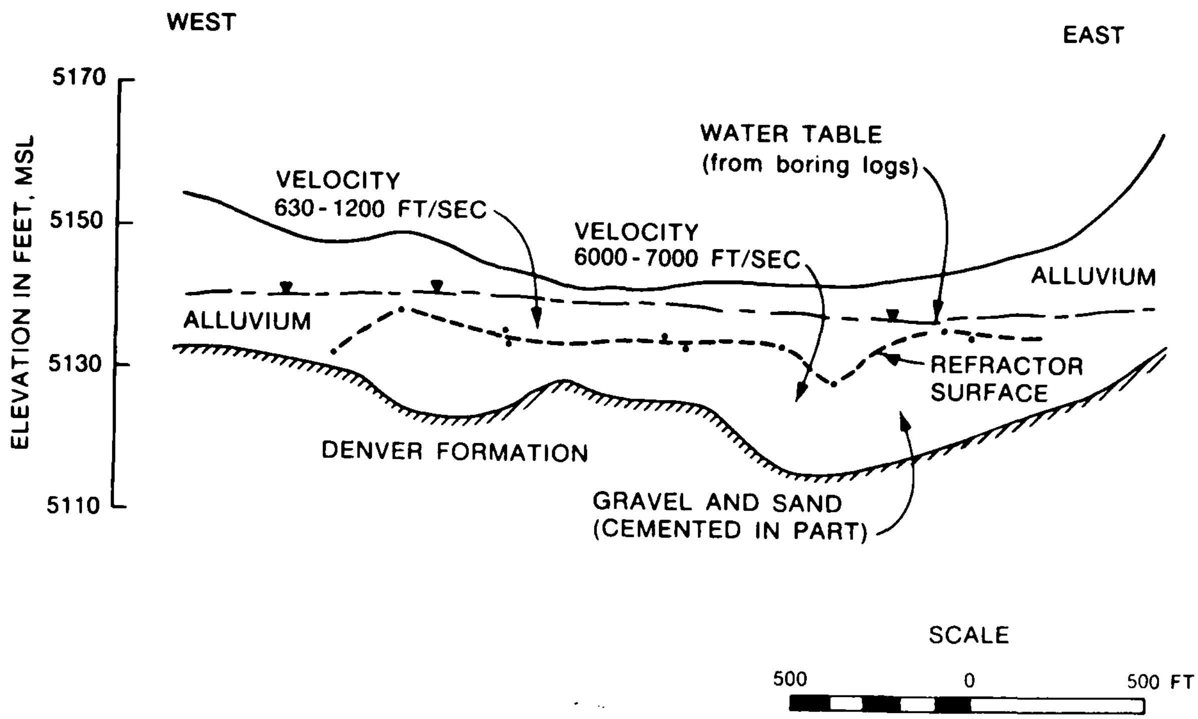


Figure 5. Time-distance plots showing a two-layer refraction system along the northern boundary of Rocky Mountain Arsenal

the extension plots fit a straight line with a high correlation, indicating that sufficient P-wave velocity contrasts did not occur between the Denver and Arapahoe formations to identify the contact. This lack of contrast is understandable because the characteristics and environment of deposition of these formations are similar. The survey was also unable to detect the thin saturated sand layers in the Denver, which illustrates blind zones.

What does this survey tell us? In simple terms, the subsurface geology is a key to the success or failure of a geophysical survey. Prior knowledge of geologic conditions can also contribute to the type or types of geophysical surveys that should be used to successfully locate ground water.

How do we improve our techniques for detecting ground water? We need to develop a predictive technique for identifying subsurface conditions in areas of interest and to identify the degree of geologic constraints exhibited against geophysical techniques.

GROUND-WATER AVAILABILITY IN SOUTHWEST ASIA--EVALUATION
OF GEOLOGIC AND HYDROLOGIC DATA

by

Dr. Robert L. Laney*

## Introduction

Many of the items discussed in this Ground-Water Detection Workshop were identified in a report by the Defense Science Board Water Support Task Force final report, "Water Support to U. S. Forces in an Arid Environment." Surface geophysical methods and remote sensing techniques received most consideration as potential ground-water detection tools. Little consideration in that report was given to evaluating the available hydrogeologic data in the areas of interest. Therefore, the purposes of this paper are to:

a. Stress the need for compilation of the available geologic and hydrologic information before geophysical or remote sensing methods are used.

b. Show that a considerable amount of geologic and hydrologic data presently exist, and that these data could be used to prepare ground-water availability maps.

c. Suggest procedures for utilizing the geologic and hydrologic data in evaluating ground-water supplies.

Examples from ground-water reports on the Arabian Peninsula area and Libya are shown to illustrate types of data that are available and how they could be used.

## Value and Use of Geologic and Hydrologic Data

Geologic knowledge of an area with attendant appreciation of hydrologic principles is essential to any ground-water prospecting activity. This knowledge can often lead to an early determination of the potential for producing the required amounts of ground water for a particular purpose or to locate areas where sufficient quantities of ground water will not be found, which could be as valuable to logistical planning as a positive determination.

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The geologic and hydrologic framework is essential to interpret the results of geophysical and remote sensing investigations conducted to evaluate the ground-water resources of an area. Geophysical and remote sensing techniques can contribute to the success of ground-water prospecting only if a geologic framework exists; without reference to geology, these techniques simply cannot find or detect ground water with any degree of certainty. The importance of a thorough evaluation of geologic and hydrologic data in any water prospecting program should not be underestimated.

## Sources of Geologic and Hydrologic Data

Potential sources of geologic and hydrologic data in Southwest Asia include the following:

- a. Reports resulting from technical cooperation programs of US Government agencies.
- b. Publications of United Nations (UN) organizations.
- c. Articles from geologic and hydrologic journals.
- d. Reports and data from consultants who performed technical investigations for countries in the region.
- e. Reports and data from petroleum companies.

A sampling of bibliographic references, as well as a few examples of ground-water availability maps for the Arabian Peninsula and Libya, will be presented in this paper.

US Government agencies, including the Corps of Engineers, Bureau of Reclamation, and the Geological Survey (USGS), have had technical cooperative programs involving geology or hydrology with countries of Southwest Asia. Bibliographic entries of geologic and hydrologic reports resulting from USGS technical cooperation with 12 countries of Southwest Asia are shown in Table 1. This information was obtained from reports by Bergquist (1976); Bergquist, Tinsley, and Upton (1979); and Heath and Tabacchi (1968). Currently, the USGS has data collection and resource evaluation activities in Saudi Arabia. Other reports have been prepared by US Government agencies for the Agency for International Development (AID) and the UN. An example is the report "Near East Water Resources Study," which was prepared by the US Department of the Interior, Bureau of Reclamation and the USGS (1970). This report, an appraisal of the water resources of eight countries in the

Near East, includes an analysis of present water use and potential for water development.

A report recently published by the UN (1982), entitled "Ground Water in the Eastern Mediterranean and Western Asia," discusses physiography, geology, hydrogeology, and water quality in 17 countries. "Ground Water in Africa," published by the UN (1973), contains a general overview of Africa's ground-water resources and their utilization, methods of exploration and exploitation, and a country-by-country discussion of geology and ground-water occurrence. A few of the countries of Southwest Asia are discussed.

One of the most detailed ground-water availability reports, entitled "Survey and Evaluation of Available Data on Shared Water Resources in the Gulf States and the Arabian Peninsula," covering three major aquifers over a 1.7 million-$km^2$ area of Southwest Asia, was recently published by the Food and Agriculture Organization of the United Nations (1979). This three-volume report contains more than 750 pages and 14 maps and covers the Kuwait area, the eastern part of Saudi Arabia, Bahrain, Qatar, and the United Arab Emirates-Oman area. Available publications and unpublished data were used to:

a. Delineate the type, thickness, distribution, and water-bearing characteristics of the sedimentary deposits in the region.

b. Show the regional ground-water flow directions.

c. Show geochemistry of the ground water.

Figure 1, a much reduced copy of one of the maps, shows piezometric contours and isopachs. A full-scale part of the map is shown in Figure 2, and the explanation is shown in Figure 3. Because of the scale, the maps provide only a generalized representation of the hydrologic data. However, more detailed hydrogeologic data can be obtained from tables for more localized or site-specific investigations.

Ground-water availability and quality in Libya are shown in two maps from a report by Jones (1964) (Figures 4 and 5). Configuration of the ground-water surface, depths to ground water, types of principal aquifers, and chemical quality of ground water are discussed in the report. The information contained on these maps gives an estimate of drilling depths and rock types that would have to be drilled to obtain potable ground water.

A search of the geoscience database, GeoRef (covers geologic and hydrologic literature from professional journals and other sources), for

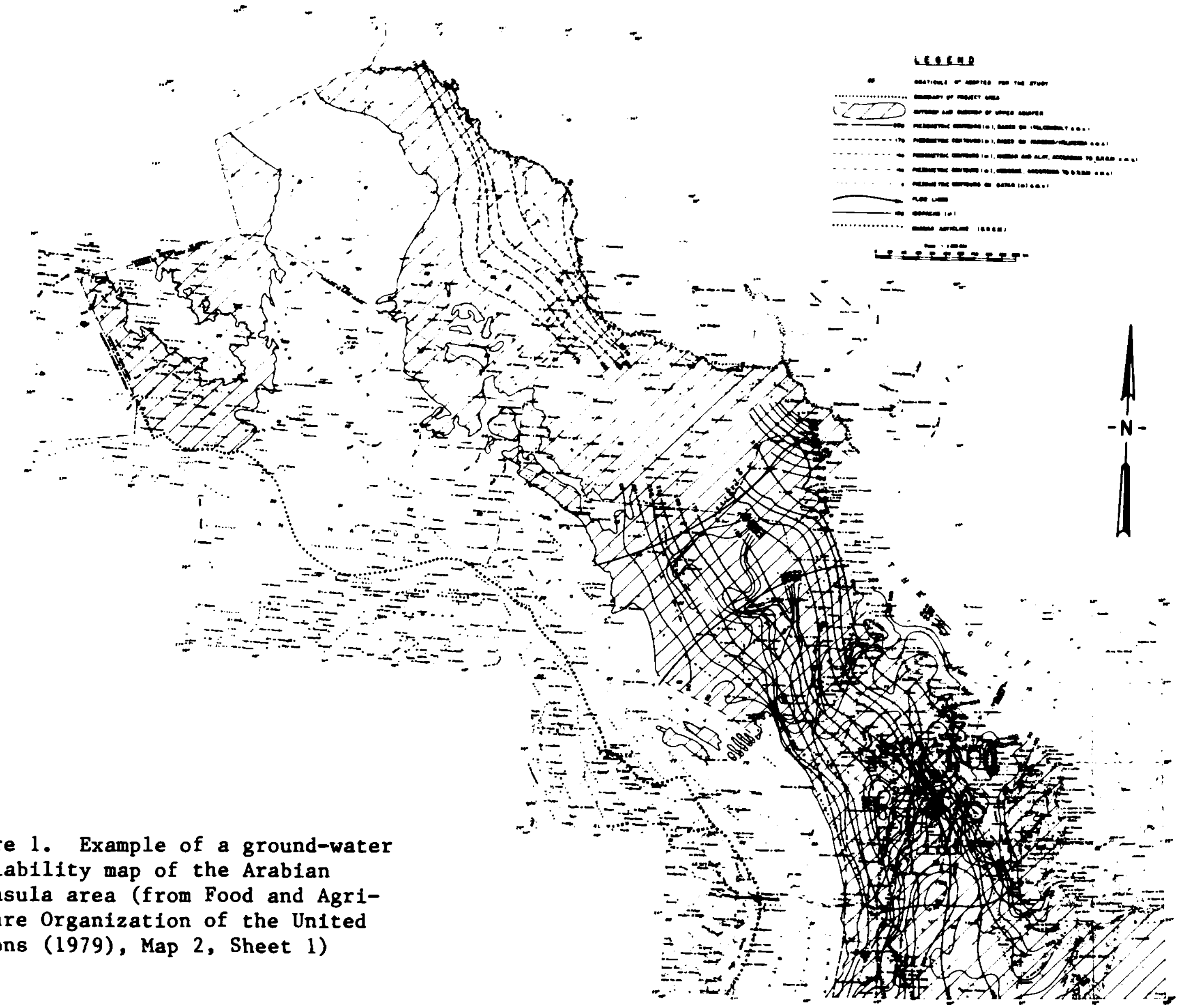


Figure 1. Example of a ground-water availability map of the Arabian Peninsula area (from Food and Agriculture Organization of the United Nations (1979), Map 2, Sheet 1)

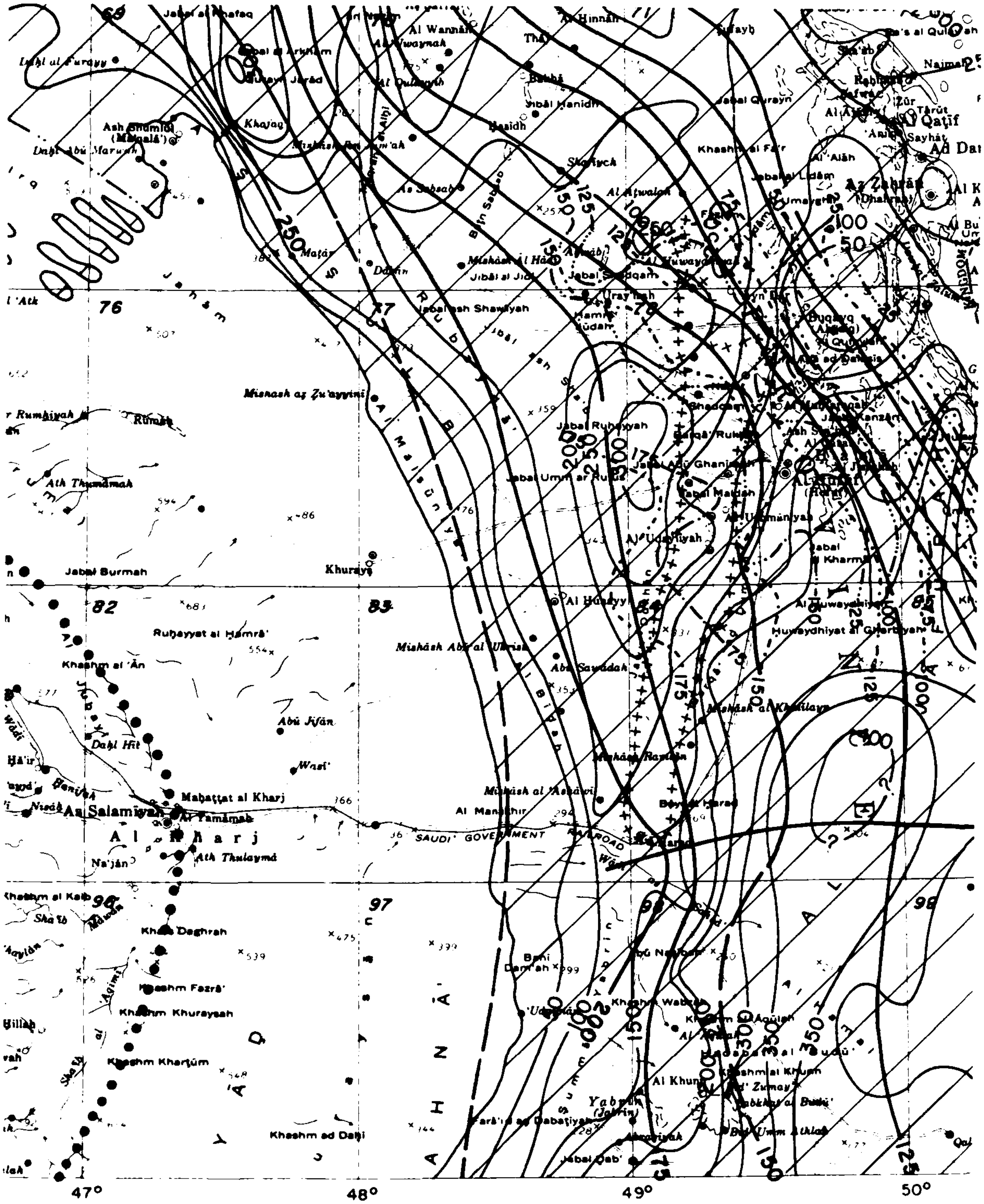


Figure 2. Full-scale part of the ground-water availability map shown in Figure 1 (from Food and Agriculture Organization of the United Nations (1979), Map 2, Sheet 1)

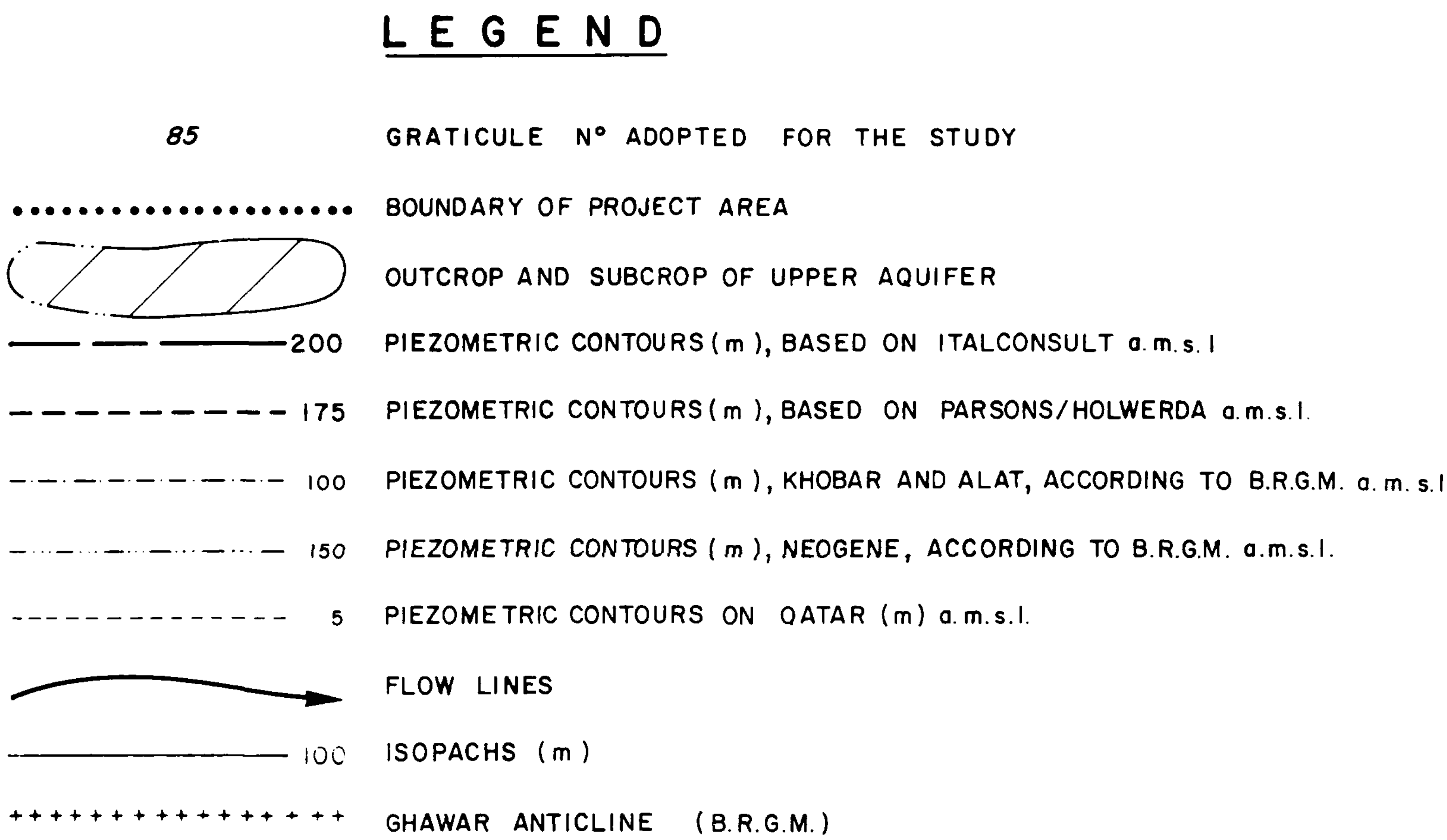


Figure 3. Explanation for the ground-water availability map shown in Figures 1 and 2 (from Food and Agriculture Organization of the United Nations (1979), Map 2, Sheet 1)

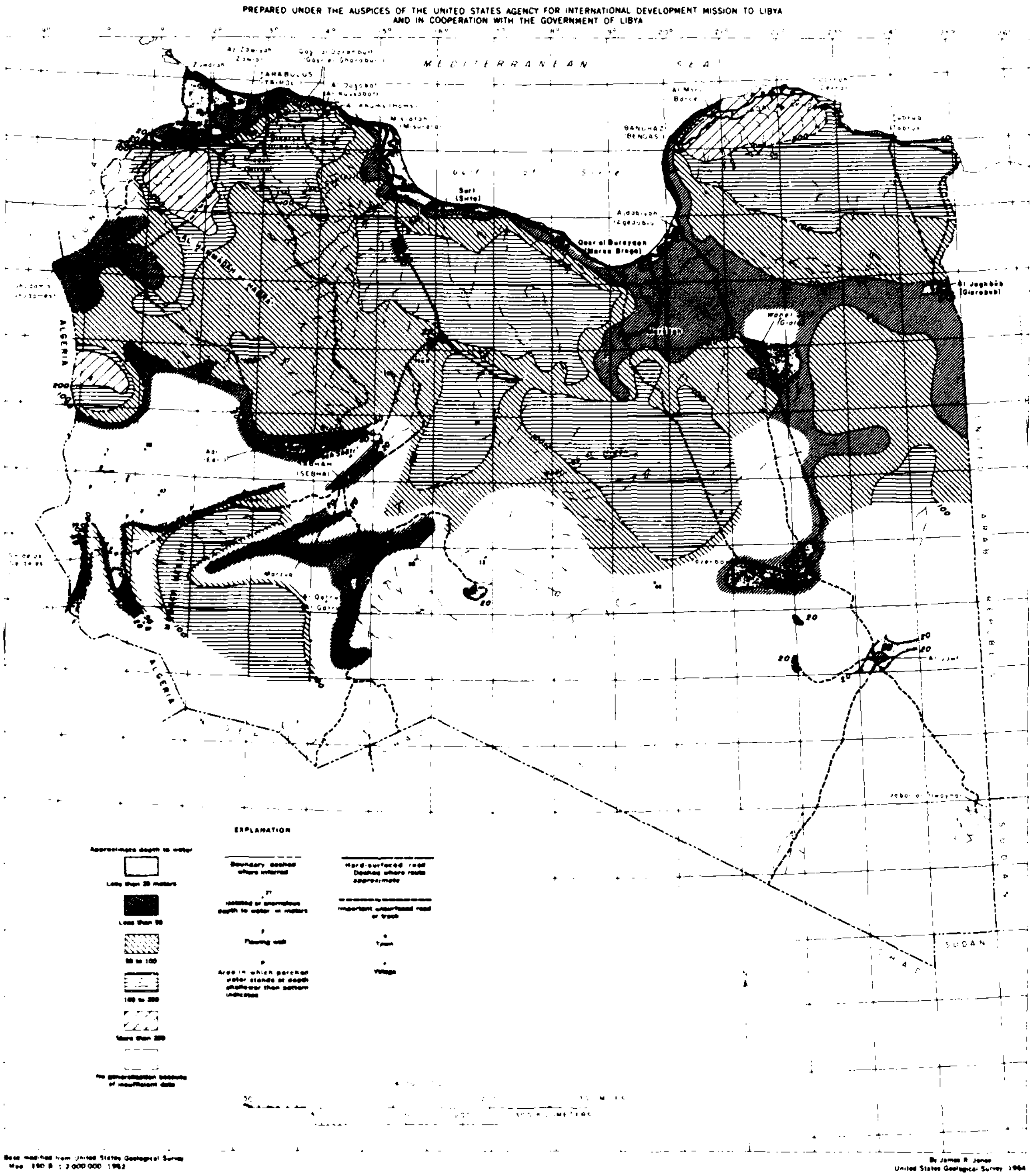


Figure 4. Example of a ground-water availability map in Libya--depth below land surface to the top of the most available or commonly used ground-water bodies (from Jones (1964), Figure 2)

te of the art, the reliability of an interpretation of surface geophysical a was highly dependent on the skill level of the personnel taking and erpreting the data. The desired specialized training level of 2 weeks .ted in the DLOA cannot be met with present-day systems.

Opinion varied within the group as to how much training was needed. To 'elop the capability to conduct the tests and perform interpretations with : aid of a minicomputer, a bright high school graduate could require from 3 6 months of intensive field and classroom training. The most difficult ·t of the training would be data interpretation. However, the capability to :ognize errors in the data, to make complex data interpretations, and to ercise judgment in recording geophysical data and in using the geologic :abase requires nothing less than a trained geophysicist or the equivalent. : lack of concensus was not with regard to the skill level required to iieve each capability, but rather as to the minimum capability needed.

The group addressed the need for a geophysical capability in the context resource allocations. In areas where water is believed to be within 300 ft the surface, exploratory drilling with lightweight equipment could be ster than geophysical techniques and would definitely be more reliable and apler.

A microcomputer and a user-friendly, nearly failure-proof data process- ; and interpretation program are especially needed when the party chief and :a analyst are not well trained. While programs do exist, they were written : use by geophysicists and cannot account for many of the errors a less lled individual could make or for all of the possible geologic conditions. :ee possible skill levels were discussed:

a. A geophysicist as field party chief and data analyst.

b. Technicians as field party chiefs and a geophysicist as data analyst, located a few hours away, who could conceivably handle data from several field parties.

c. A technician as field party chief and data interpreter.

le the latter skill level would be simplest for the Army from a personnel ewpoint, the group could endorse only the second level. Because of a total :k of experience with skill level c., research is needed to find out if it ı be made to work (i.e., to develop the necessary data interpretation tools I to determine the probable levels of associated error).

## Geophysical Requirements

| Group Members | Agency Affiliation |
|---|---|
| Dr. Paul F. Hadala, Chairman | WES |
| Dr. Steven A. Arcone | CRREL |
| CPT(P) W. T. Broadwater | MERADCOM |
| Dr. Dwain K. Butler | WES |
| Dr. Adel A. R. Zohdy | USGS |
| Dr. Robert L. Laney | USGS |
| CPT Robert Thompson | MERADCOM |
| Mr. John G. Collins | WES |
| Mr. Joseph R. Curro, Jr. | WES |
| Mr. William L. Murphy | WES |
| MAJ William E. Norton | WES |

### Discussions

In addition to geophysical methodologies and the associated proposed research priorities, several other topics were addressed in the group discussions. These included: (a) the DLOA for a Subsurface Water Detector, (b) the need for a geophysical exploration capability, (c) the training and skill levels required to conduct geophysical surveys, and (d) the need for a geologic database as an aid to geophysical data interpretation.

The concensus of the group regarding the DLOA was that the state of the art of geophysics does not permit the development of a detector with anything like a 90-percent success rate. All geophysical measurements discussed are indirect; they do not measure the presence of water and/or the permeability of a stratum containing water. What is measured are physical responses and characteristics indicative of the geologic structure and stratigraphy and certain mechanical or electrical properties of the layers. Trained interpreters can use these data to rule out the possibility of developable water at a given depth in certain circumstances. In other cases, they can infer that the data are compatible with the presence of developable water; however, subsurface conditions other than ground water can often be interpreted with the same set of geophysical data. Additionally, the group contended that, with the present

| Proposed Priority | Task | Cost $000 1st Year | 2nd Year | 3rd Year | Out Years |
|---|---|---|---|---|---|
| | **Near Term (Continued)** | | | | |
| 3 | Develop rainfall estimation procedures for catchment size areas using satellite sensors (NOAA) and methods for integrating with time to evaluate ground-water aquifer recharge histories in inaccessible areas. | 60 | 100 | - | - |
| 4 | Conduct pilot studies to demonstrate operational potential of remote sensing techniques for providing geologic and hydrologic information required in the database. | - | 50 | 250 | - |
| 5 | Develop training course for remote sensing applications. | 50 | 100 | 200 | - |
| | **Far Term** | | | | |
| 1 | Develop methods using imaging systems to infer aquifer depth and extent (quantity of water). | - | 100 | 150 | 400 |
| 2 | Develop methods using existing imaging systems to infer ground-water quality. | - | 100 | 150 | 350 |
| 3 | Develop advanced image processing techniques to reduce the time required for image analysis for ground-water detection. | - | - | 200 | 500 |
| 4 | Evaluate advanced and emerging satellite remote sensors for ground-water detection. | - | - | 100 | 400 |
| 5 | Develop radar and longwave electromagnetic ground-water survey devices for airborne applications. | - | 150 | 200 | 300 |
| 6 | Develop application procedures for advanced weather satellite monitoring and forecasting of aquifer recharge potential. | - | - | 75 | 200 |

| Proposed Priority | Task | Cost $000 | | | |
|---|---|---|---|---|---|
| | | 1st Year | 2nd Year | 3rd Year | Out Years |
| | **DATABASE RESEARCH** | | | | |
| | **Near Term** | | | | |
| 1 | Define specific DoD database output requirements. | 35 | | | - |
| 2 | Compile user queries for water-supply planning. Evaluate existing software packages for query response generation and develop new software to fill capability gaps. | 40 | 120 | 180 | - |
| 3 | Assess existing data sources and clearly define source gaps. | 50 | 75 | - | - |
| 4 | Develop optimum scheme for providing the basic data required for the database by data type and output products required. | 30 | 150 | 100 | - |
| | **Far Term** | | | | |
| 1 | Explore advanced geographic information system packages and emerging technologies for long-term update of automated database capabilities. | - | - | 75 | 250 |
| | **REMOTE SENSING RESEARCH** | | | | |
| | **Near Term** | | | | |
| 1 | Develop guidance for optimum use of military reconnaissance sensors for rapid assessment of ground-water conditions. | 80 | 130 | 150 | - |
| 2 | Adapt existing Landsat/USGS type analyses to provide regional geologic and hydrologic information for ground-water database development. | 100 | 200 | 200 | - |

The second level of database information content would be of a much broader nature and oriented toward the total water-supply problem. Included would be data on geologic stratigraphy, existing water-supply and distribution systems, surface and subsurface water resources, water wells, transportation networks, and surface terrain. Potential applications would be as follows:

a. Stratigraphic data would be used by the geophysicist as an aid for isolating areas for the conduct of geophysical surveys and in the actual interpretation of geophysical response data.

b. All of the data could serve as input for water-supply related planning queries. Possible examples are, "What size force could be supported by water resources within area X?" "Could water be distributed from point A to point B most efficiently by pipeline(s) or trucks?" or "What mix of water-supply equipment is required to supply force B in area C?"

Some time was spent in discussing the acquisition of input data for the automated system. The USGS presentations given during the general session clearly showed that considerable data, particularly geologic and hydrologic, are available from oil companies, private consultants, and Government agencies that have conducted investigations in Southwest Asia; however, these data would necessarily have to be supplemented using remote sensing procedures. With reference to database inputs from existing sources, the group also recommended that considerable care be devoted to establishing exact specifications on types and formats. Without such specifications, the volumes and formats of data acquired could make the encoding process an almost impossible task.

## Proposed research priorities

On the basis of presentations and discussions in the general and working group sessions, proposed research priorities within the near- and far-term time frames were established. Proposed priorities and associated cost estimates for the first, second, third, and out years for tasks defined under both database and remote sensing research efforts are as follows:

Mr. Gerald K. Moore USGS

MAJ Edward Wages USMC

MAJ Ron Allari LOGCEN

Discussions

Initial group discussions were directed toward the database problem area. The group noted that for almost 2 years the Rapid Deployment Joint Task Force (RDJTF), now US Central Command (CENTCOM), has supported an automated water database concept, with provisions for ground water-related information. Further, the DSB report to the Joint Chiefs of Staff (JCS) on water support includes recommendations for a water resources database. Group members representing the user community (REDCOM, RDJTF, LOGCEN, USAF, and USMC) agreed that a database was essential to their needs. Because a multiservice requirement exists, the types and formats of outputs for such a database should be defined and specified at the DoD level using the Corps of Engineers' database study* s a point of departure. However, the specific agency that should be assigned responsibility for the planning and implementation of the database was not identified.

As a result of presentations made during the general session of the Workshop, working group members stated that the database should contain two levels of information. One level of information would be restricted to the definition of ground-water sources. This information, displayable in map form, would serve to delineate the areal positions of ground-water aquifers and depth categories (e.g., 0-200, 200-600, and 600-1500 ft); in addition, associated data on quality, yield, aquifer and overlying geologic materials, and some overall measure of ground-water potential could be included at this level. This information would have several uses:

a. To select specific, high-potential areas for geophysical surveys and analyses.

b. To select specific areas for drilling where the depth to water is so shallow and the probability of finding ground water so high that geophysical surveys are not warranted.

c. To formulate operational plans.

d. To conduct analyses of water supply equipment requirements.

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* Calkins, H. W., and Johnson, T. R. 1981. "Military Hydrology; Report 4, Evaluation of an Automated Water Data Base for Support to the Rapid Deployment Joint Task Force (RDJTF)," Miscellaneous Paper EL-79-6, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

## GROUP DISCUSSIONS AND IDENTIFICATION OF PROPOSED RESEARCH PRIORITIES

On the afternoon of 13 January 1982, Workshop attendees were divided into two groups for the purpose of establishing proposed research priorities. One group, chaired by Dr. Link, focused on database and remote sensing requirements, and the other group, chaired by Dr. Hadala, on geophysical requirements. Prior to the group meetings, Dr. Link provided the following procedural guidelines:

a. Each group was tasked with setting proposed research priorities in their respective topic areas. Recommended research efforts were to be either basic or exploratory (i.e., of a 6.1 or 6.2 nature).

b. Separate proposed priorities were to be established for near- and far-term periods. Near-term efforts were defined as those that could be completed in 3 years or less, and far-term, as those that would require 4 or more years for completion.

c. Estimates of research costs and time requirements were to be made, if possible, for each effort defined.

The attendees agreed that requirements set forth in the Engineer School Draft Letter of Agreement (DLOA) for a Subsurface Water Detector and the conclusions and recommendations of the Defense Science Board (DSB) report "Water Support to US Forces in an Arid Environment" would be reviewed and evaluated in the context of the Workshop proceedings.

Below are summaries of the two group meetings, including lists of group members, résumés of the discussions that transpired, and summary tabulations of proposed research priorities with associated time and cost estimates.

### Database and Remote Sensing Requirements

| Group Members | Agency Affiliation |
|---|---|
| Dr. Lewis E. Link, Jr., Chairman | WES |
| Dr. Ming Tseng | OCE |
| Mr. John H. Shamburger | WES |
| LTC John Pellek | USAF |
| MAJ Steve TerMaath | USAF |
| LTC Paul Barcomb | REDCOM |
| Mr. Martin Fadden | HQDA |
| Mr. Melvin B. Satterwhite | ETL |
| Mr. Ponder Henley | ETL |

Table 3

Hypothetical Summary of Ground-Water Availability Information

| Items | Subareas Within Country A | B | C | etc.→ |
|---|---|---|---|---|
| Single aquifer | X | | | |
| Multiple aquifer | | X | X | |
| Unconfined aquifer, shallow | X | X | | |
| Unconfined aquifer, deep | | | X | |
| Confined aquifer, shallow | | X | | |
| Confined aquifer, deep | | X | X | |
| Fresh water, shallow | X | | | |
| Fresh water, deep | | X | X | |
| Brackish water, shallow | | X | | |
| Brackish water, deep | | X | | |
| Contaminated aquifer | | X | | |
| Unconsolidated aquifer | | X | | |
| Consolidated aquifer | | X | | |
| Soil type | | | | |
| Gravel | X | | X | |
| Sand | X | X | X | |
| Silt | | | | |
| Rock type | | | | |
| Limestone | | X | | |
| Shale | | | | |
| Sandstone | | | | |
| Granite | | X | | |

Table 2

Reports in the Geoscience Database, GeoRef, 1967 to 1981, Covering Countries in Southwest Asia

| Country | Number of Reports |
|---|---|
| Saudi Arabia | 680 |
| Libya | 679 |
| Turkey | 2196 |
| Iran | 1400 |
| Egypt | 1778 |
| Yemen | 65 |
| Jordan | 491 |
| Israel | 1338 |
| Aden | 324 |
| Kuwait | 84 |
| Bahrain | 28 |
| Iraq | 532 |
| Total | 9595 |

Table 1

Geologic and Hydrologic Reports Resulting From US Geological Survey Technical Cooperation with Countries in Southwest Asia, 1940-1979

| Country | Number of Reports |
|---|---|
| Saudi Arabia | 374 |
| Libya | 55 |
| Turkey | 44 |
| Iran | 20 |
| Egypt | 19 |
| Yemen | 19 |
| Jordan | 7 |
| Israel | 5 |
| Aden | 3 |
| Kuwait | 3 |
| Bahrain | 2 |
| Iraq | 2 |
| Total | 553 |

Bergquist, W. E., Tinsley, E. J., and Upton, V. S. 1979. "Bibliographic Supplement to US Geological Survey Bulletin 1426, 1975 to June 1979," Open-File Report 79-1518, US Department of the Interior, Geological Survey, US Government Printing Office, Washington, DC.

Food and Agriculture Organization of the United Nations. 1979. "Survey and Evaluation of Available Data on Shared Water Resources in the Gulf States and the Arabian Peninsula" (3 volumes), Rome.

Heath, J. A., and Tabacchi, N. B. 1968. "Bibliography of Reports Resulting from US Geological Survey Participation in the United States Technical Assistance Program, 1940-67," US Department of the Interior, Geological Survey, Bulletin 1263, US Government Printing Office, Washington, DC.

Jones, J. R. 1964. "Ground-Water Maps of the Kingdom of Libya," Open-File Report, US Department of the Interior, Geological Survey.

United Nations. 1973. "Ground Water in Africa," Department of Economic and Social Affairs, New York.

__________. 1982. "Ground Water in the Eastern Mediterranean and Western Asia," Department of Technical Co-operation for Development, New York.

US Department of the Interior, Bureau of Reclamation and Geological Survey. 1970. "Near East Water Resources Study; Part 1, Regional Reports, and Part 2, Country Reports," unpublished report prepared for US Department of State and the Agency for International Development.

c. Transmissivities.

d. Hydraulic heads and flow directions.

e. Depths to the top of confined (artesian) aquifers.

f. Water quality data.

These maps usually will require technical interpretation by persons versed in hydrogeologic principles. In some cases, if the information is to be used by planners or those responsible for logistical operations, the ground-water availability information that is shown on the maps will have to be condensed into a less technical summary. Various schemes can be used to summarize this information. One method is shown in Table 3.

An area covering a country or part of a country could be divided into geographical or political subareas or grid cells, and the important hydrogeological characteristics listed under the subareas of the country where they apply. The items in Table 3 could be more specific than those shown; "shallow" and "deep," for example, could be replaced with specific values or a range in depth values. Rock type terms could be supplemented with information on accessibility and on the relative difficulty of drilling. A written summary of the availability of ground water in each subarea could be prepared and used with the tabulated summary (Table 3). Potential well yield for each aquifer and a more detailed definition of water quality can be addressed in the written summaries for each subarea. The summarized data could be adapted to a computerized storage and retrieval system that contains other pertinent data on the area.

The preparation of the ground-water availability maps will be manpower-intensive if a large area is to be evaluated in a short time. The areas to be evaluated should be prioritized to allow efficient use of manpower. Experienced hydrologists and geologists must be used in the evaluation if the endeavor is to be successful.

## Literature Cited


Bergquist, W. E. 1976. "Bibliography of Reports Resulting from US Geological Survey Technical Cooperation with Other Countries, 1967-74," letin 1426, US Department of the Interior, Geological Survey, US Government Printing Office, Washington, DC.

12 countries in Southwest Asia yielded a total of 9,595 report entries for the period 1967 through 1981 (Table 2). The GeoRef reports cover a broad spectrum of the geosciences. Some reports do not apply to ground-water availability--for example, reports on solid-earth geophysics. However, other entries, such as reports on economic geology, while not dealing directly with hydrogeology, could provide the hydrogeologist with background geologic data and estimations of the distribution and water-bearing characteristics of rocks.

A large amount of geologic and hydrologic data from consultants and from petroleum companies in the Arabian Peninsula area was used in the preparation of the report by the Food and Agriculture Organization of the United Nations (1979). However, the availability of data from these two sources often varies from country to country.

The examples given above were shown and discussed to indicate the types of hydrogeologic information that is or could be available for countries in Southwest Asia. The amount and quality of data vary greatly and in some areas may not be sufficient to adequately predict the availability of ground water. Identifying the areas for which little information is available or known would be an important first step in the assessment of ground-water potential. In many areas, the available data are adequate to determine in advance the potential for obtaining an adequate ground-water supply, without the use of geophysical or remote sensing methods. Assessment of available hydrogeologic data in Southwest Asia should have a high priority in determining the probability of finding sufficient quantities of ground water.

## Methods for Determining Ground-Water Availability

Ground-water availability can be shown on a map or series of maps. A base map having uniform scale and symbols should be used for the data to achieve continuity between countries or regions. A database should be used, or developed, to store, retrieve, and update information as required. Ground-water availability maps can provide some or all of the following kinds of data:

a. Types and numbers of aquifers present.

b. Types of rock materials that would be drilled, depths to water or depths to potable water, potential well yields.

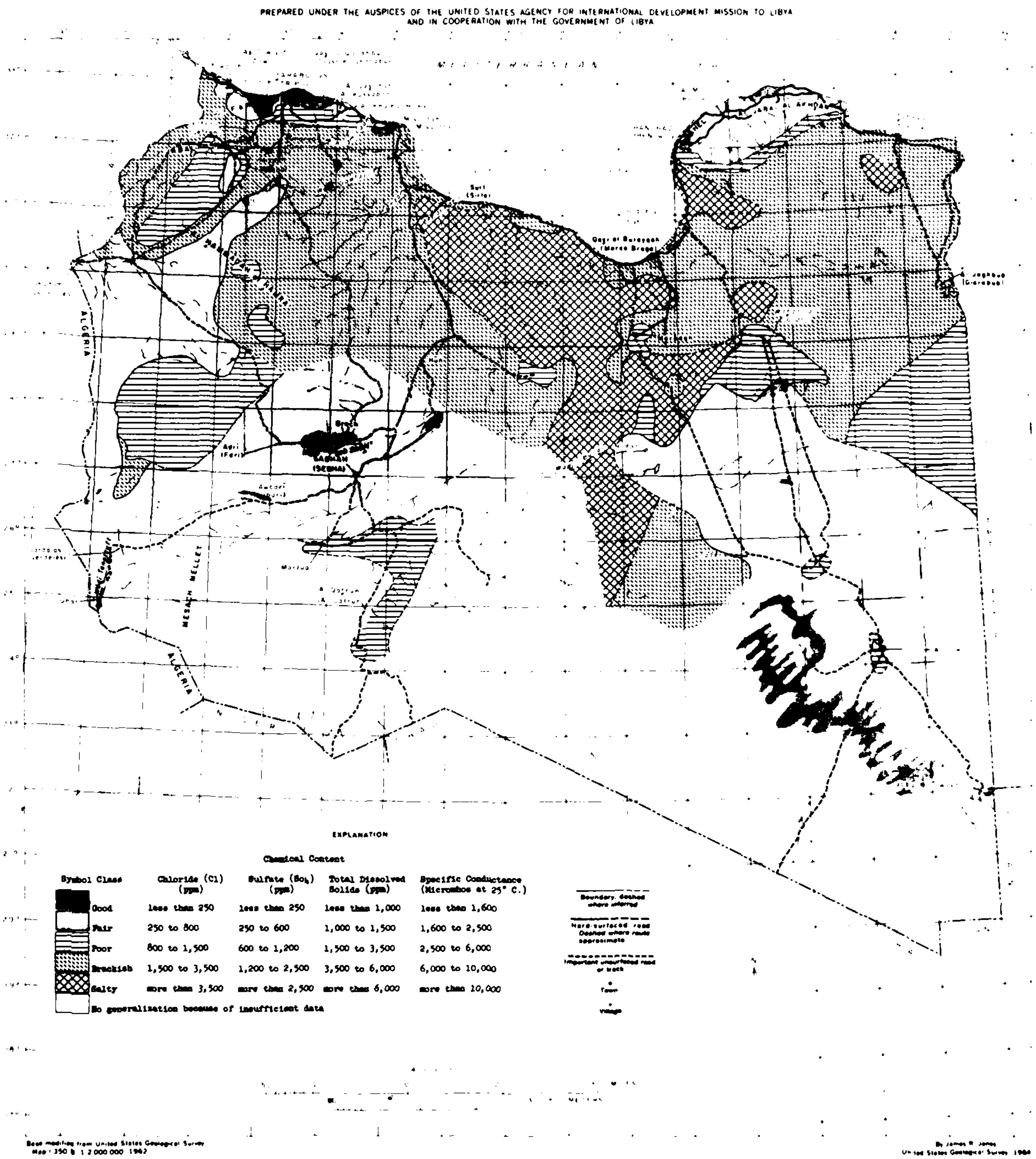


Figure 5. Example of a ground-water availability map in Libya--chemical quality of the most available or commonly used ground-water bodies (from Jones (1964), Figure 4)

Stratigraphic, lithologic, and structural geologic information, as well as the constraints imposed by various geologic configurations on geophysical surveys, should be included in a database. Although a considerable amount of geologic data is available for certain areas of the world, many of these data are likely not in a form that could be used by geophysicists without some modification. Data for other areas of interest are sometimes limited or of insufficient detail. Research is needed to identify in specific terms various configurations of real world geologic conditions (stratigraphy, lithology, and structure) and the constraints these characteristics place on geophysical surveys. Using these constraints as guidelines, procedures need to be developed for categorizing geologic conditions in areas of interest from available geologic publications and for interpreting conditions in unmapped areas from remote images, topographic maps, etc. These types of data are needed as input if a database system is to be complete and usable by individuals involved in planning, conducting, and interpreting phases of a geophysical survey.

The group concluded that seismic refraction and electrical resistivity (Schlumberger array) are the only geophysical methods that the state of the art will permit fielding as ground-water detection aids in the near term, assuming that the training versus professional interpreter problem is solved. Both resistivity and seismic surveys should be conducted at a given location because the inferences drawn from both can usually be used to make more precise interpretations than could be drawn from either method alone. Hence, there is a need for both methodologies in the Theatre of Operations. Issue was taken with the DSB recommendation for near-term exploitation of ground-penetrating radar (GPR) because the depth of penetration may be on the order of 200 ft or less; in certain tactical environments, such shallow depths may not be suitable for the mission. Additionally, GPR data require skilled interpretation. Swept-frequency radar systems offer some advantages that should be explored in the far term.

Several state-of-the-art and emerging geophysical techniques have potential in the far term for application to the ground-water detection problem. The group recommended feasibility assessment studies to investigate these state-of-the-art methods and identify the most promising. Geophysical methods that should be included are: electromagnetic methods, including time domain and swept-frequency radar methods; magnetotelluric methods; induced

polarization; and seismic reflection. The effective use of ground penetrators was not considered feasible, even in the far term.

Proposed research priorities

Proposed geophysical research priorities within the near and far terms and associated cost estimates for the first, second, third, and out years are presented below:

| Proposed Priority | Task | Cost $000 1st Year | 2nd Year | 3rd Year | Out Years |
|---|---|---|---|---|---|
| | **Near Term** | | | | |
| 1 | Upgrade and simplify automated and manual methods of data processing and interpretation for both seismic refraction and electrical resistivity methods in order to maximize potential for success by nonprofessional data interpreters. | 100 | 50 | - | - |
| 2 | Evaluate trainability/error trade-off for nonprofessional analyst and interpreter for both seismic and resistivity methods. | 100 | 50 | - | - |
| 3 | Develop procedures to reduce the time required for field operations associated with seismic and resistivity methods. | - | 150 | 100 | - |
| 4 | Develop techniques for identifying and categorizing geologic constraints on geophysical systems. Apply these techniques to selected world areas for database input. | 50 | 275 | 200 | - |
| 5 | Determine whether an air-conditioned van is needed to house both commercial seismic and resistivity equipment and computers for protection against saline conditions, dust, and temperature effects. | - | - | 70 | - |
| 6 | Develop training literature and training program based on results from Tasks 1 and 2. | - | 100 | 100 | - |

| Proposed Priority | Task | Cost $000 1st Year | 2nd Year | 3rd Year | Out Years |
|---|---|---|---|---|---|
| | **Far Term** | | | | |
| 1 | Evaluate and field test electromagnetic, seismic reflection magnetotelluric, and induced polarization methods and select candidate procedure(s). | 100 | 100 | 200 | 200 |
| 2 | Further develop procedure(s) and establish training requirements for data interpretation. | - | - | 100 | 400 |
| 3 | Develop and evaluate prototype swept-frequency radar system for rapid ground-water surveys down to moderate depths (i.e, 600 ft). | - | 100 | 150 | 400 |